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THE EFFECT OF PITCH ON FORCE AND MOMENT CHARACTERISTICS OF FULL-SCALE PROPELLERS OF FIVE SOLIDITIES

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NACA

WASHINGTON

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THE EFFECT OF PITCH ON FORCE AND MOMENT CHARACTERISTICS OF FULL-SCALE PROPELLERS OF FIVE SOLIDITIES

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SUMMARY

An investigation was conducted in the NACA 20-foot propeller-research tunnel to determine the effect of variations in angle of pitch on the aerodynamic characteristics of several propeller combinations. Two-, three-, four-, and six-blade single-rotating propellers and a six-blade dual-rotating propeller were tested on a nacelle with the thrust axis pitched at angles of 0°, 5°, 10°, and 15°. The propellers, which were 10 feet in diameter, were tested at blade angles of 25° and 45°. The force and moment coefficients of the propellers were obtained for these conditions.

The results indicate that the propulsive efficiency decreases as the angle of pitch increases. The loss due to pitch increased with increased solidity and was greater at the higher blade-angle settings.

The vertical force increased with the angle of pitch throughout the entire V/nD range, whereas the yawing moment increased with pitch only in the low V/nD range. The yawing moment, torque reaction, and side force nearly vanished with dual rotation, but the vertical force increased. A greater solidity increased the vertical force and generally increased the yawing moment. A greater blade angle generally increased the forces and the moments measured.

INTRODUCTION

Pitching the thrust axis of a propeller alters its thrust, power (or torque), and efficiency characteristics and, in addition, subjects the propeller to vertical and horizontal forces as well as pitching, yawing, and rolling moments. Of these effects, the vertical force, yawing moment, and change in efficiency due to pitch influence the performance and stability of an airplane to an appreciable extent.

Both theoretical and experimental studies of the effects of a propeller operating at an inclined attitude have been undertaken at various times. (See references 1, 2, and 3.) Most of the previous empirical work was done with model propellers having only two or three blades and operating in a low V/nD range. Lesley, Worley, and Moy, in 1935-36, made wind-tunnel experiments in the Stanford University wind tunnel with a model propeller. With the propeller in yaw, they measured the effects of oblique air currents on the propeller force and moment characteristics for several different blade-angle settings.

The present investigation was undertaken in order to extend previous work to include tests of full-scale propellers having different numbers of blades and in order to determine the effect of pitch on dual rotation. The propellers were tested at positive angles of pitch θ of 0°, 5°, 10°, and 15°. Four different blade combinations, consisting of two-, three-, four-, and six-blade tractor propellers were used to determine the effect of pitch and solidity. The six-blade condition included both single- and dual-rotating propellers. The investigation in these tests of the complete V/nD range involved the use of seven "new" coefficients in the range of negative thrust and power. New coefficients, such as T_c, were formed by multiplying standard coefficients, such as C_T, by the factor $(nD/V)^2$. The project was carried out in the 20-foot propeller-research tunnel during May and June 1941 with a set-up that had been previously used for testing dual-rotating propellers.

The data contained in this report may be applied to propellers in yaw by rotating the reference axes 90°.

APPARATUS AND METHODS

The NACA 20-foot propeller-research tunnel, in which the investigation was conducted, is described in reference 4. The tests were run with airspeeds ranging from zero to 110 miles per hour.

The propeller-drive mechanism (fig. 1) was enclosed in a streamline nacelle, which had been used in several previous investigations (reference 5). The test arrangement, with the principal moment arms from the scale reactions to the propeller origin indicated, is shown in outline in figure 2. A photograph of the set-up is given in figure 3. At the angle of zero pitch the center line of the propeller-nacelle combination coincided with the wind axis of the tunnel. The angle of pitch of the nacelle was varied by means of a jackscrew in the rear strut.

Five 10-foot-diameter propellers were employed (Hamilton Standard drawing numbers 3155-6, right hand, and 3156-6, left hand). The blade-form curves are shown in figure 4. The hubs of the two- and the three-blade single-rotating propellers were located in the rear spinner. The six-blade single- and dual-rotating propellers were composed of 2 three-blade propellers mounted in tandem in the front and rear spinners. The four-blade propeller was made up with 2 two-blade propellers, one on the front and the other on the rear spinner.

The net thrust was measured in the usual manner by a thrust balance. The torque was measured by the spring-dynamometer and Selsyn device combination mentioned in reference 5. Vertical forces were measured by lift balances located at the corners of the floating frame in the balance house, and side forces were determined from balance readings at the front and rear of the floating frame. Values of the pitching and yawing moments were determined from suitable combinations of the lift, the drag, and the side force. A comparison of the values of $-C_Q \cos \theta$ and actual rolling moment obtained from the lift and the side-force balances resulted in a decision to use torque values transposed to the wind axis in place of rolling moment. (See fig. 5.)

The propellers were driven by alternating-current induction motors and the speed was controlled by varying the frequency of the current supplied to the motors. The single-rotation tests were run with the motors coupled together. For the dual-rotation tests the speed of the two propellers was kept equal by means of a frequency-converter apparatus and checked with a synchroscope. The dual-rotation tests were made with the rear propeller blades set to provide approximately the same torque at peak efficiency as the front propeller blades.

Propeller speed was varied from a maximum speed of about 550 rpm to approximately zero to cover the range beyond zero thrust, that is, to the point where $n = 0$ or $V/nD = \infty$. The Reynolds number was about 1,000,000 at peak efficiency for the propellers set at 25° at 0.75 radius. Typical plots of propeller-coefficient results and vertical-force and moment coefficients are given in figures 6, 7, 8, and 9.

RESULTS

The extreme range of propeller-operating conditions covered in this investigation has made it convenient to use two types of coefficients for presenting the data. The usual coefficients,

Thrust coefficient $C_T = \dfrac{T}{\rho n^2 D^4}$

Power coefficient $C_P = \dfrac{2\pi Q}{\rho n^2 D^5}$

Efficiency $\eta = \dfrac{C_T}{C_P} \dfrac{V}{nD}$

are used on the propeller curves up to the position of zero thrust. The force and moment coefficients have been put into similar form covering the range from $V/nD = 0$ to $V/nD = 1.0$,

Side-force coefficient $C_Y = \dfrac{F_Y}{\rho n^2 D^4}$

Vertical-force coefficient $C_Z = \dfrac{F_Z}{\rho n^2 D^4}$

Rolling-moment coefficient $C_l = \dfrac{-Q \cos\theta}{\rho n^2 D^5}$

Pitching-moment coefficient $C_m = \dfrac{M}{\rho n^2 D^5}$

Yawing-moment coefficient $C_n = \frac{N}{\rho n^2 D^5}$

where

T sum of measured thrust of propeller-nacelle combination and drag of body measured separately

ρ air density

n rotational speed

D propeller diameter

Q propeller torque

η efficiency

V airspeed

F_Y side force

F_Z vertical force

θ angle of pitch

M pitching moment

N yawing moment

The value $\frac{-C_Q \cancel{\cos\theta}}{\cancel{\rho n^2 D^5}}$ was substituted for $C_{l_1} = \frac{L}{\rho n^2 D^5}$, where L is rolling moment, because the torque was easily obtainable from the spring-dynamometer readings and resulted in more consistent data. (See fig. 8.) The difference in the values of C_{l_1} and $-C_Q \cos\theta$ was probably caused by strut interference on the nacelle. For values beyond the point of zero thrust, the thrust and power coefficients were multiplied by $(nD/V)^2$, which gives the second form,

$$T_c = C_T\ (nD/V)^2 = \frac{T}{\rho V^2 D^2}$$

$$2\pi Q_c = C_P\ (nD/V)^2 = \frac{2\pi Q}{\rho V^2 D^3}$$

Similarly, new coefficients were formed for the other forces and moments by multiplying C_Y, C_Z, C_l, C_m, and C_n by $(nD/V)^2$.

$$L_c = \frac{-Q \cos \theta}{\rho V^2 D^3}$$

$$M_c = \frac{M}{\rho V^2 D^3}$$

$$N_c = \frac{N}{\rho V^2 D^3}$$

$$Y_c = \frac{F_Y}{\rho V^2 D^2}$$

$$Z_c = \frac{F_Z}{\rho V^2 D^2}$$

The parameter V/nD was changed to nD/V at the value of 1.0, at which the two parameters coincide, to keep the complete range covered by the coefficients down to a reasonable size. The position of zero propeller speed ($V/nD = \infty$, $nD/V = 0$) was difficult to obtain but was approached by means of reversing switches on the propeller-motor circuit.

The values for the new propeller coefficients were also plotted against nD/V beyond the value of zero thrust to the position where $n = 0$.

In order to eliminate the effect of the slipstream reactions on the body and the supporting struts, the side force, the vertical force, the pitching moment, and the yawing moment have been plotted with the values for zero pitch deducted from the values obtained for the pitched propellers. It was assumed that the slipstream reactions on the body and the supporting struts would remain constant with changes in pitch and also that these forces and moments should be zero for zero pitch.

All coefficients of forces and moments were computed with the origin at the intersection of the propeller axis and its plane of rotation, with the result that these values could be easily transferred for stability computations on an airplane. For the dual-rotating propeller the origin was located midway between the front and the rear hubs. The reference axis in all cases was the wind axis of the tunnel.

For rapid reference the figures showing the propeller force and moment characteristics are listed as follows:

Efficiency

Figures 10-14	Effect of pitch on efficiency
Figures 15-16	Effect of solidity on efficiency
Figures 17-18	Effect of dual rotation on efficiency

Thrust

Figures 19-23	Effect of pitch on thrust
Figures 24-25	Effect of solidity on thrust
Figures 26-27	Effect of dual rotation on thrust

Power

Figures 28-32	Effect of pitch on power
Figures 33-34	Effect of solidity on power
Figures 35-36	Effect of dual rotation on power
Figures 37-40	Individual power curves

Side Force

Figures 41-42	Effect of pitch on side force
Figure 43	Effect of solidity on side force
Figure 44	Effect of dual rotation on side force

Vertical Force

Figures 45-46	Effect of pitch on vertical force
Figure 47	Effect of solidity on vertical force
Figure 48	Effect of dual rotation on vertical force

Rolling Moment

Figures 49-50	Effect of pitch on rolling moment
Figure 51	Effect of solidity on rolling moment
Figure 52	Effect of dual rotation on rolling moment

Pitching Moment

Figures 53-54	Effect of pitch on pitching moment
Figure 55	Effect of solidity on pitching moment
Figure 56	Effect of dual rotation on pitching moment

Yawing Moment

Figures 57-58	Effect of pitch on yawing moment
Figure 59	Effect of solidity on yawing moment
Figure 60	Effect of dual rotation on yawing moment

DISCUSSION

The effect of the four parameters - pitch, solidity, dual rotation, and blade angle - on the various propeller force and moment coefficients is presented in the following discussion:

Efficiency.--The effect of pitch on efficiency for each propeller may be observed in figures 10 to 14. The loss in efficiency $\Delta\eta$ due to pitch appeared, in general, to be negligible for angles of pitch of 5° for the 25° blade angle; but a decrease of 0.01 or 0.02 in efficiency became evident at the blade angle of 45° for propellers having three or more blades. For an angle of pitch of 10°, the loss varied from 0.01 to 0.03 at $\beta = 25°$ and from 0.02 to 0.05 at $\beta = 45°$. At the highest angle of pitch tested, $\theta = 15°$, the loss in efficiency was considerable, ranging from 0.02 to 0.05 at $\beta = 25°$ and from 0.05 to 0.12 at $\beta = 45°$. Each additional 5° increment in pitch nearly doubled the loss in efficiency from the previous increment; it is, therefore, to be expected that beyond the range investigated, that is, for angles larger than $\theta = 15°$, the loss would be quite high. This conclusion is confirmed in references 1 and 2.

Figures 15 and 16 are comparisons of the efficiencies for different solidities. These figures indicate that the efficiency was decreased with an increase in solidity over the entire V/nD range, except at very low values of V/nD. At the higher blade angle (45°) the effect of pitch on efficiency was more pronounced for high-solidity propellers than for low-solidity ones.

A study of the efficiency curves for the dual-rotation condition (figs. 17 and 18) reveals that, although the dual-rotating propellers were the most efficient, they experienced about the same loss in efficiency from being pitched 10° as the single-rotating propellers.

Thrust.- The maximum thrust in both the positive and negative range decreased with pitch, whereas the value of V/nD for zero thrust increased with pitch (figs. 19 to 23).

The increment of thrust due to increasing solidity was generally less for 10° pitch than for 0° (figs. 24 and 25).

Figures 26 and 27 show that dual rotation resulted in an increase in thrust over the single-rotation condition, but the gain was less for 10° than for 0° pitch.

Power.- The effects of pitch, solidity, and dual rotation on the power coefficients are generally the same as on the thrust coefficients (figs. 28 to 40); further discussion is, therefore, unnecessary.

Side force.- Figures 41 and 42 indicate that the side-force coefficient, which was usually small, generally increased slightly in a negative direction with increases in pitch, particularly for low values of V/nD. There were no consistent trends of the side-force coefficient for the negative thrust range of V/nD. There was no consistent variation of side force with solidity, as may be noted in figure 43. Of interest is the fact that the side force nearly vanished with dual rotation. (See fig. 44.)

Vertical force.- The vertical force is composed of several elements: The vertical component of the thrust; a vertical reaction of the propeller due to an unbalance in torque of the blades passing through the 3 o'clock and 9 o'clock positions; and the slipstream reactions on the body. The effects of the slipstream have been eliminated by the method used in plotting the results.

In figures 45 and 46 it may be seen that the vertical force was nearly proportional to the pitch angle. At $V/nD = 0$ the vertical force was due almost entirely to the vertical component of the thrust; the part due to the other factors mentioned was negligible. As the value of V/nD increased this vertical component of the thrust would be expected to decrease nearly proportionately to the decrease in thrust; and the vertical component due to the unbalance in blade torque would be expected to increase, because of the increasing unbalance in the angle of attack of the blades passing through the 3 o'clock and 9 o'clock positions.

Figure 47 is a comparison of solidities for the vertical-force coefficient. In the pitched condition the vertical-force coefficient increased with solidity throughout the $V/nD - nD/V$ range, as would be expected.

The dual-rotation comparison (fig. 48) reveals that the dual-rotating propeller had higher vertical-force coefficients than the single-rotating propeller throughout the $V/nD - nD/V$ range, particularly in the pitched condition. This condition can be explained by the fact that the dual-rotating propeller produced more thrust than the single-rotating propeller.

Rolling moment.- The rolling-moment coefficient was but slightly affected by pitch, as may be seen in figures 49 and 50. Throughout most of the V/nD range the rolling-moment coefficient, computed from the scale readings, was slightly less than the value, $-C_Q \cos \theta$, because of the reaction of the slipstream on the supports. (See fig. 5.) A comparison of solidities for the rolling-moment coefficient (fig. 51) exhibits nothing unusual. Pitch had little effect on either the dual-rotating or single-rotating six-blade propellers, as is illustrated in figure 52. Dual rotation resulted in only a small net torque reaction because the rear propeller almost canceled the effect of the front propeller.

Pitching moment.- The measurement of pitching moment was inaccurate because it involved the use of four lift scales and a drag scale, each with a long lever arm. Although there is no consistency in the measured results regarding the effect of angle of pitch on pitching moment (figs. 53 and 54), the values are fairly small, indicating that the propeller pitching moment is negligible except for cases in which the longitudinal stability is neutral or very small. The effect of solidity on pitching moment was more clearly defined than the effect of angle of pitch (fig. 55).

The dual-rotation measurements (fig. 56) are likewise inconclusive.

Yawing moment.- At low values of V/nD the yawing-moment coefficient increased with pitch; at high values of V/nD no general trend could be detected. (See figs. 57

and 58.) As might be expected a larger number of blades resulted in larger moments. (See fig. 59.) The yawing moments nearly vanished with dual rotation (fig. 60), because the rear propeller nearly neutralized the effects of the front propeller.

CONCLUSIONS

Varying the angle of pitch of a propeller, besides changing the efficiency, thrust, and power, introduced vertical and side forces as well as pitching, yawing, and rolling moments; of these effects, efficiency, vertical force, and yawing moment have an important effect on performance and stability.

Pitching a propeller had little effect, in general, on the efficiency until the angle of pitch was greater than 5°; beyond this value of the angle of pitch, the loss became appreciable, depending upon the blade angle and the number of blades. The loss in efficiency due to pitch increased with propeller solidity and blade angle. This loss amounted to as much as 0.12 for a six-blade propeller operating at 45° blade angle and 15° angle of pitch. The loss was about the same for dual rotation as for single rotation.

The side forces and the pitching moments as found in these tests were small and except for an airplane of low stability, these forces and moments could probably be neglected.

The vertical force increased with the angle of pitch throughout the entire range of V/nD, while the yawing moment increased with pitch only in the lower part of the V/nD range.

The yawing moment, rolling moment, and side force nearly vanished with dual rotation; but the vertical force increased.

Higher solidity increased the vertical force and generally increased the yawing moment.

The forces and moments measured generally increased as the blade angle increased.

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5. Biermann, David, and Hartman, Edwin P.: Wind-Tunnel Tests of Four- and Six-Blade Single- and Dual-Rotating Tractor Propellers. NACA Rep. No. 747, 1942.

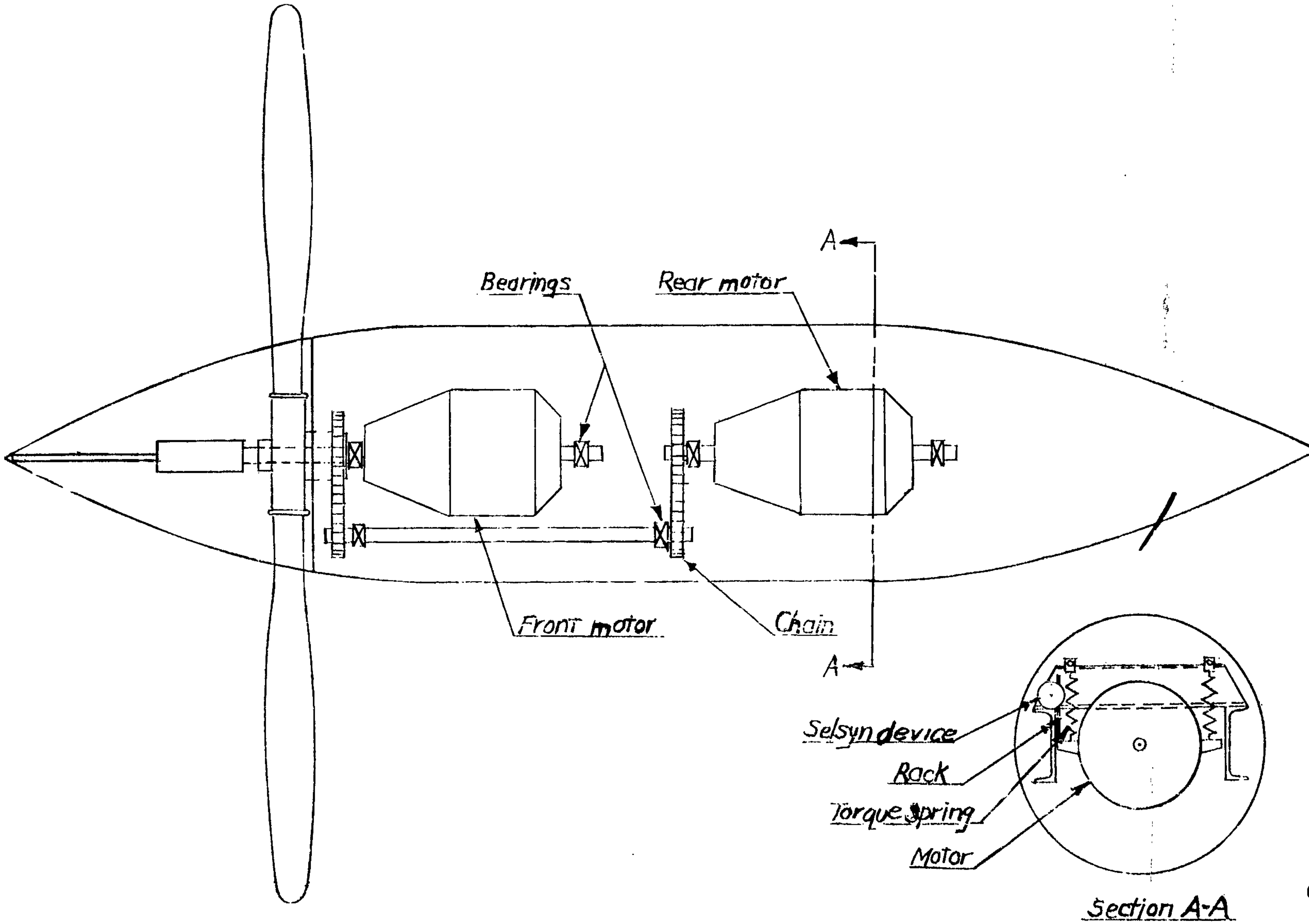

Figure 1.- Propeller-drive mechanism.

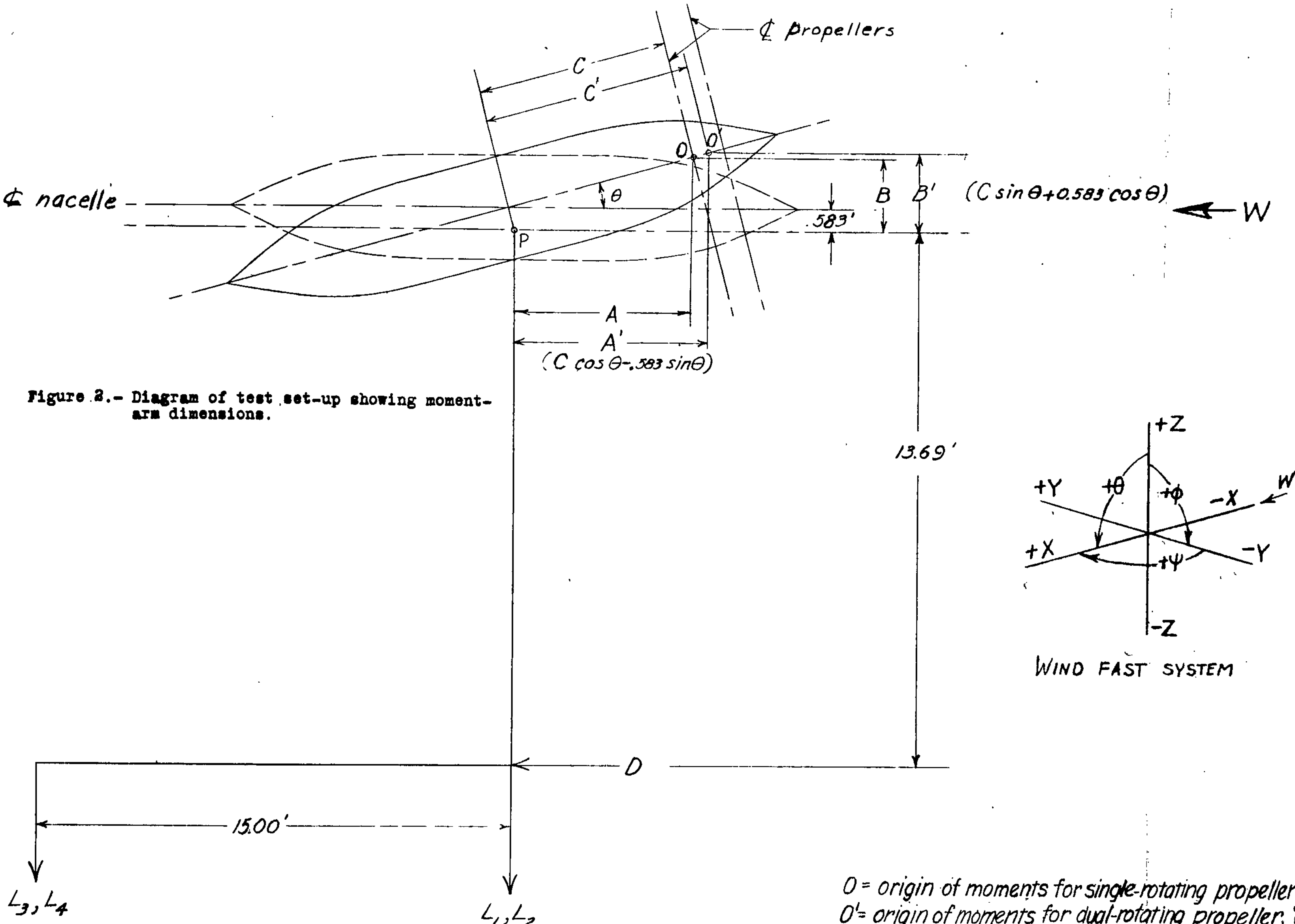

Figure 2.- Diagram of test set-up showing moment-arm dimensions.

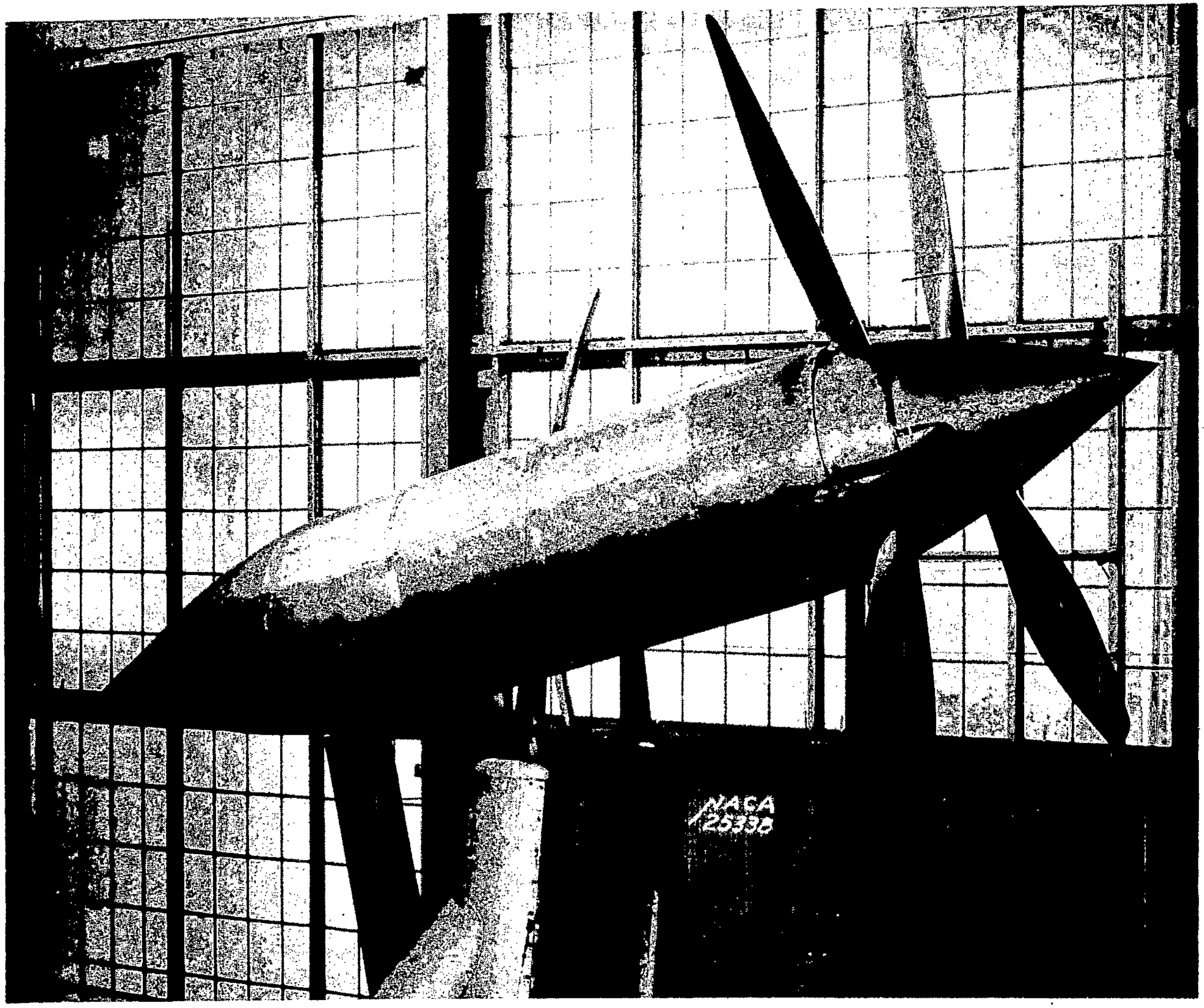

Figure 3.- Test set-up in NACA 20-foot wind tunnel.

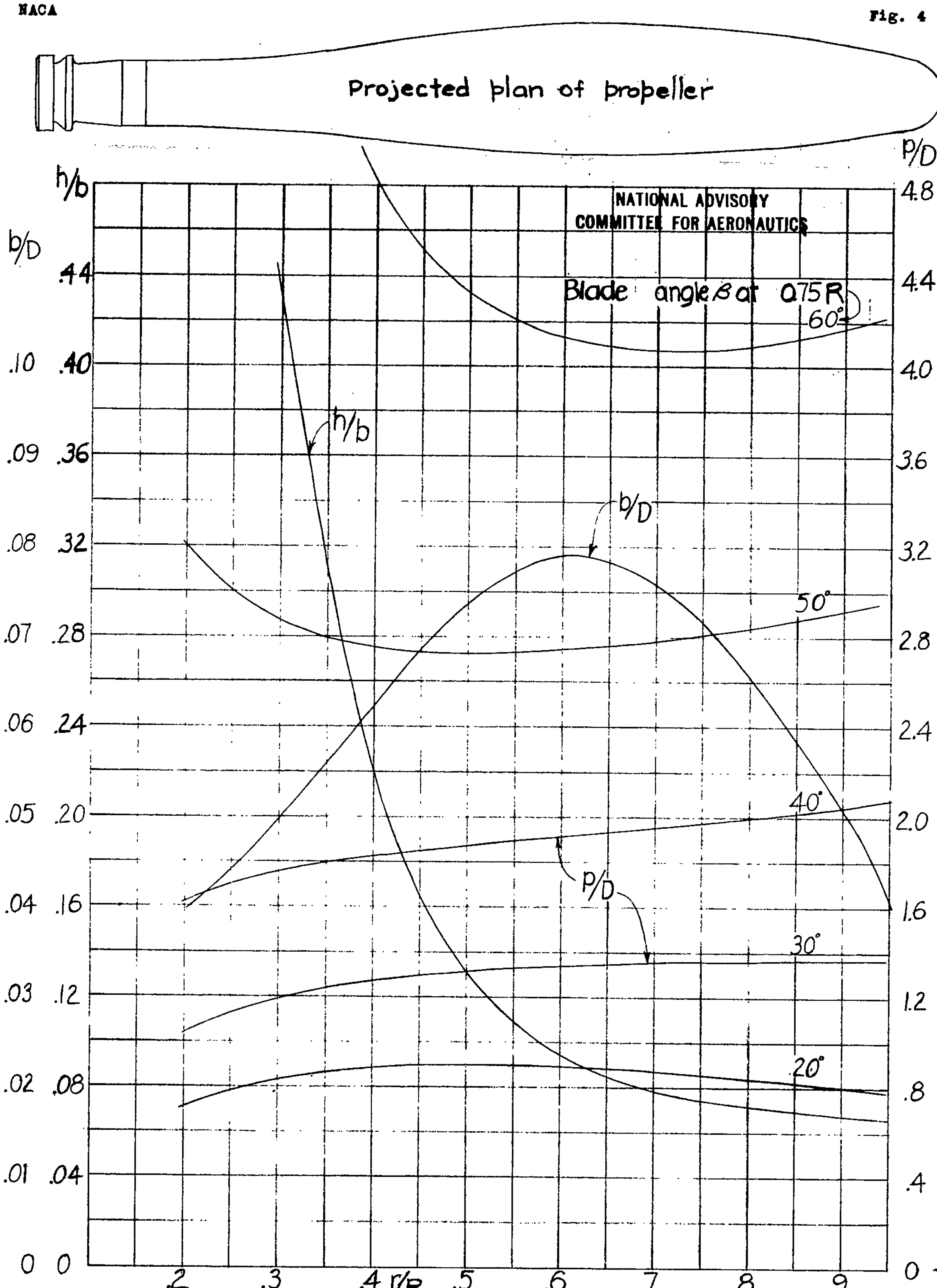

FIGURE 4.– Plan form and blade-form curves for propeller 3155-6.
D, diameter; R, radius to the tip; r, station radius; b, section chord; h, section thickness; p, geometric pitch.

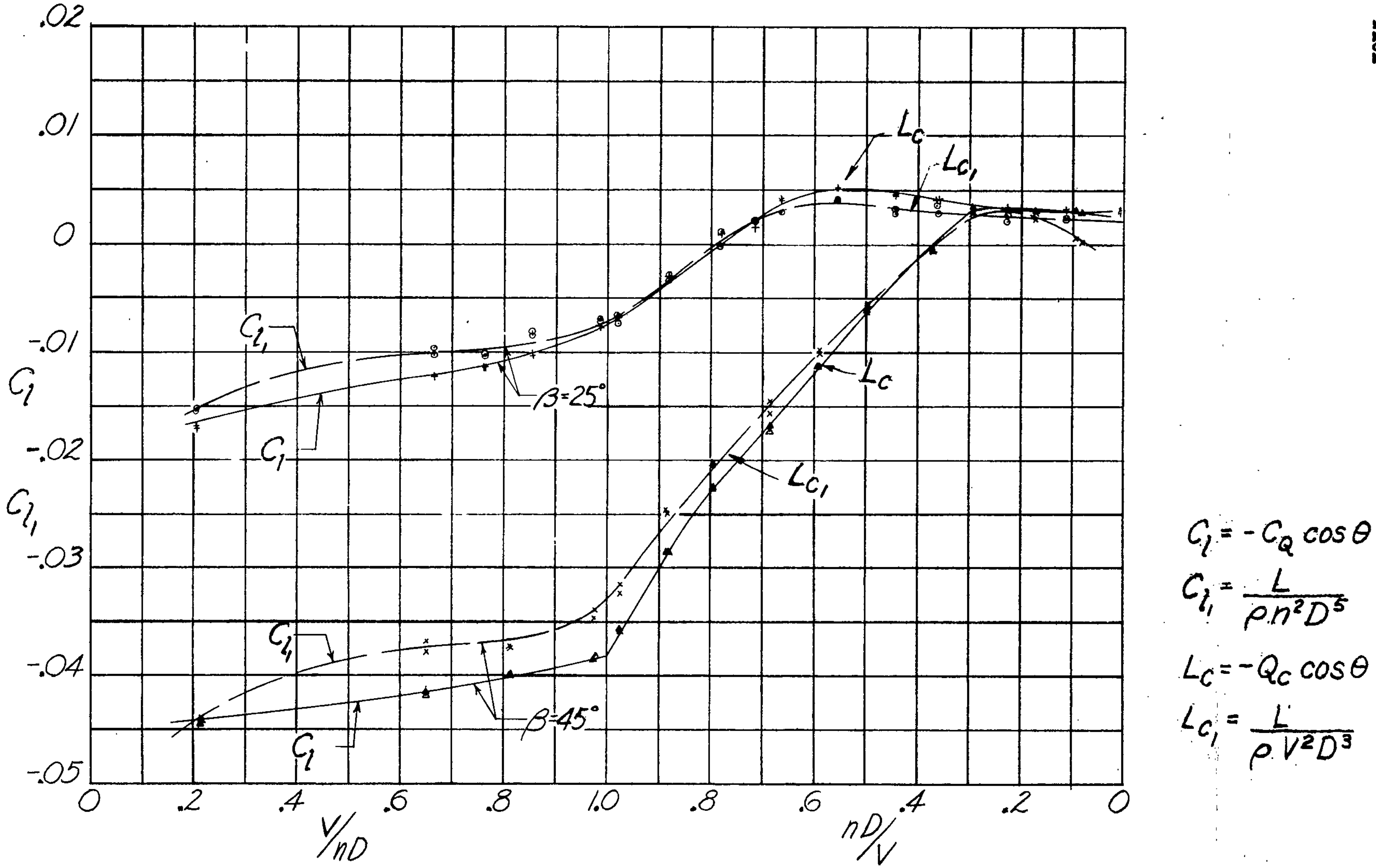

FIGURE 5.- Comparison of torque coefficient with rolling-moment coefficient for same propeller solidity, θ=0°.

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Fig. 5

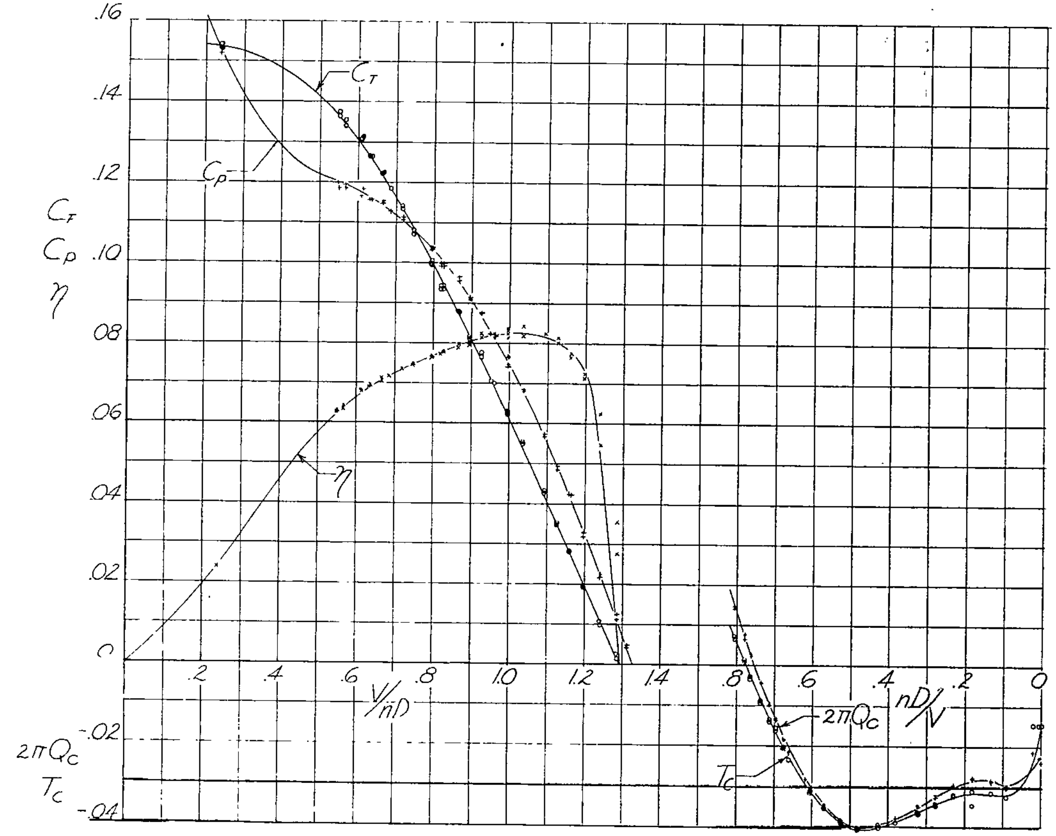


FIGURE 6.- Typical test results. Three-blade propeller; $\theta = 15°$; $\beta = 25°$.

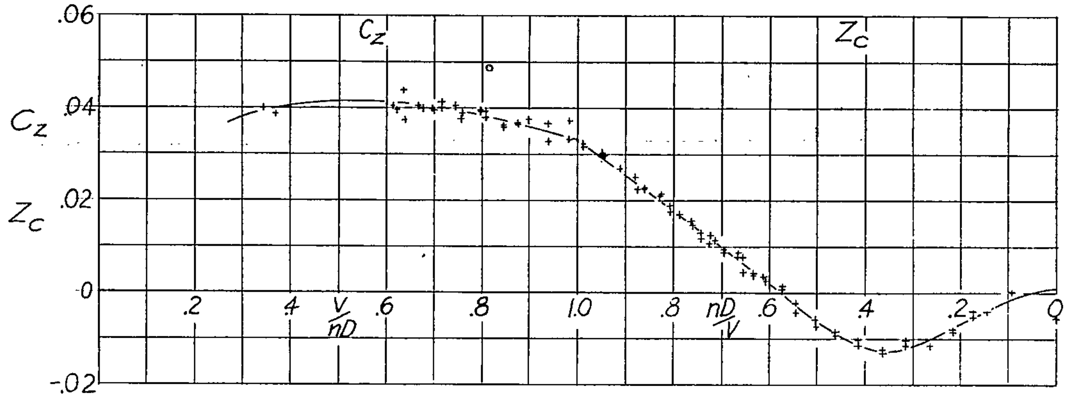


FIGURE 7.- Typical test results. Vertical-force-coefficient curve for six-blade propeller. θ=10°; β=25°.

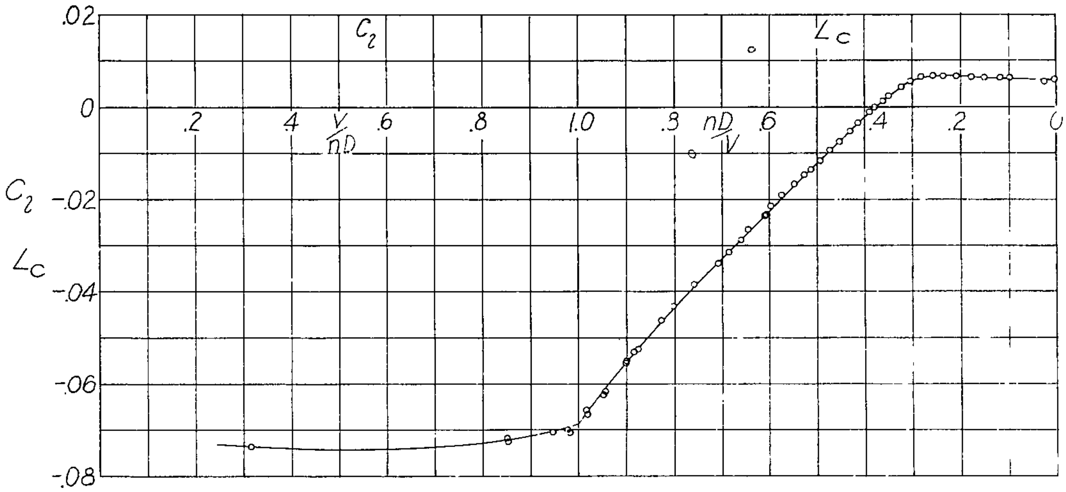


FIGURE 8.- Typical test results. Rolling-moment-coefficient curve for four-blade propeller. θ=5°; β=45°.

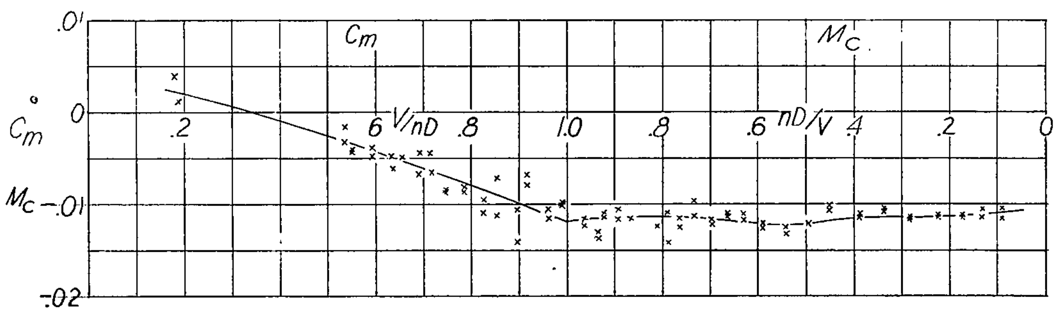


FIGURE 9.- Typical test results. Pitching-moment-coefficient curve for two-blade propeller. θ=5°; β=25°.

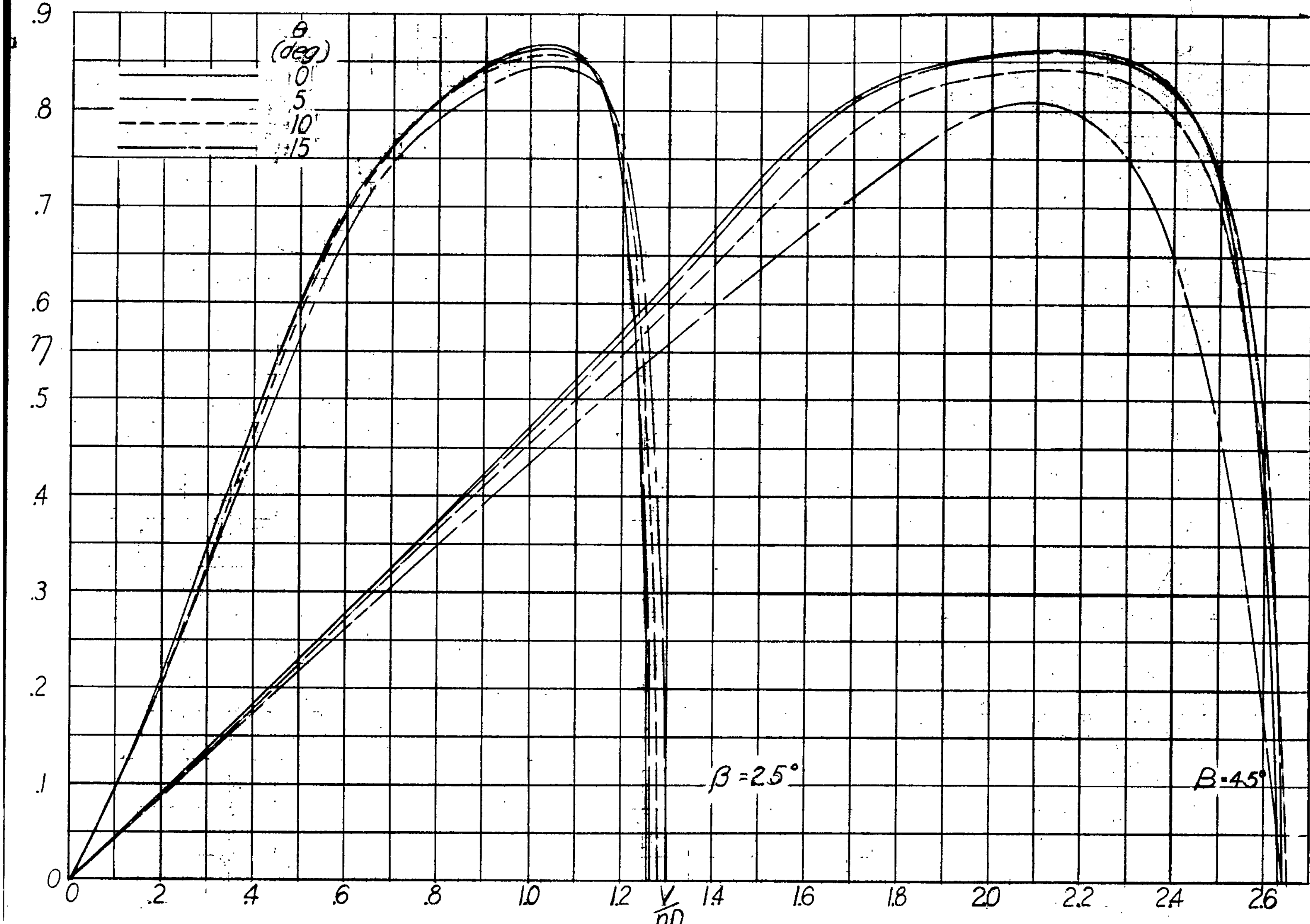
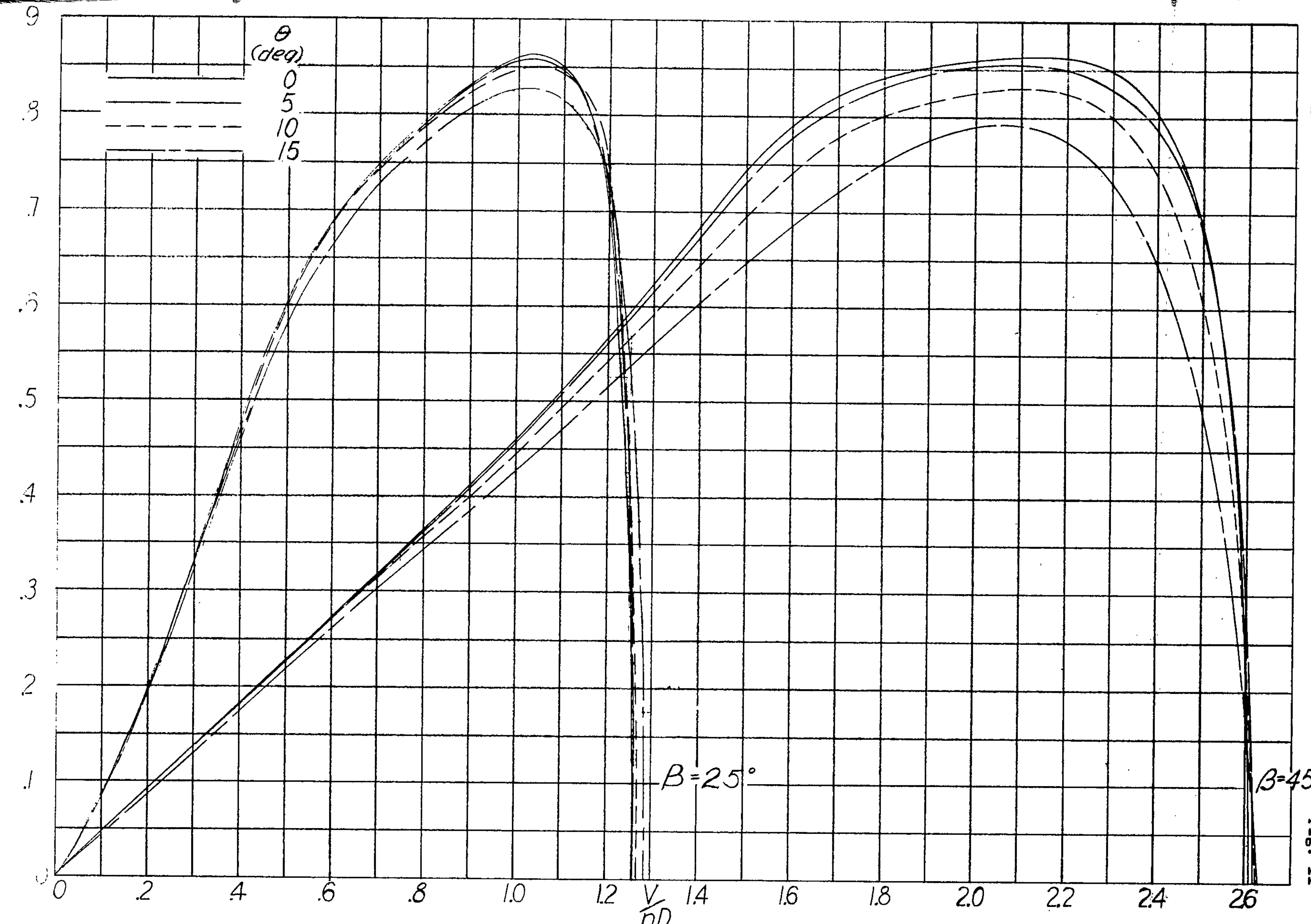


FIGURE 10.- Effect of pitch on efficiency for two-blade propeller.

NACA Fig. 10



NACA FIG. 11

FIGURE 11.- Effect of pitch on efficiency for three-blade propeller.

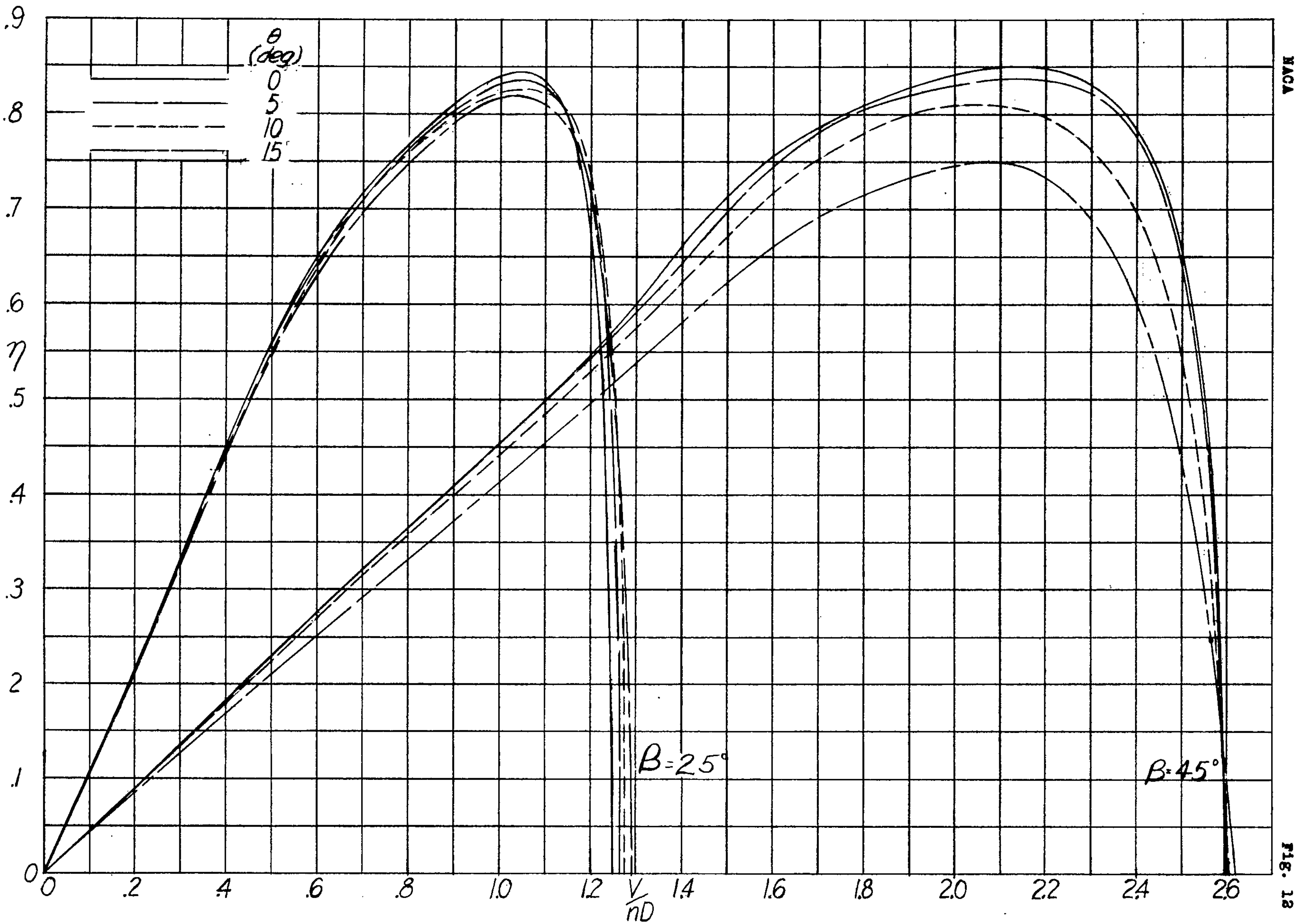


FIGURE 12.- Effect of pitch on efficiency for four-blade propeller.

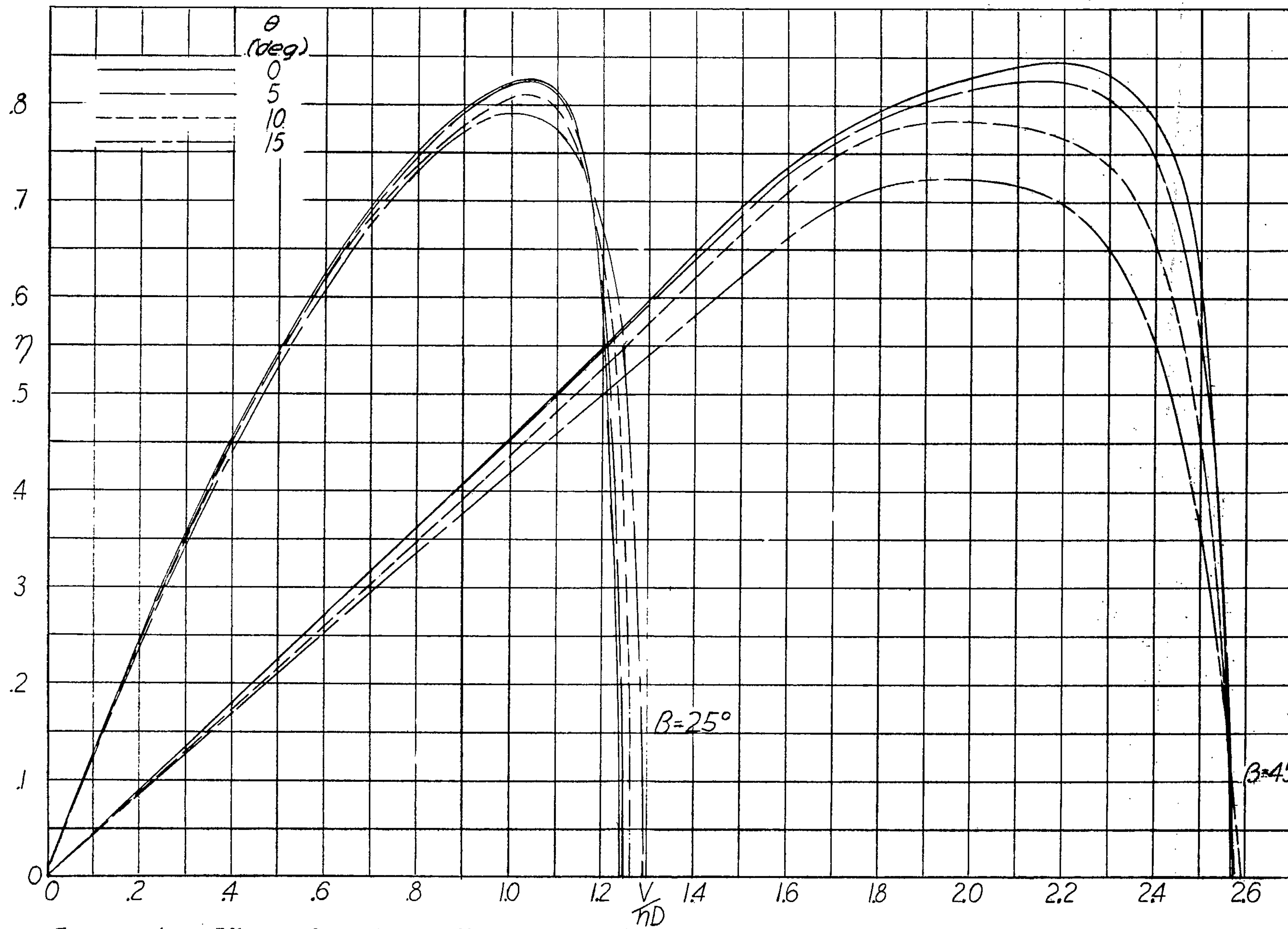


FIGURE 13.- Effect of pitch on efficiency for six-blade propeller.

NACA Fig. 13

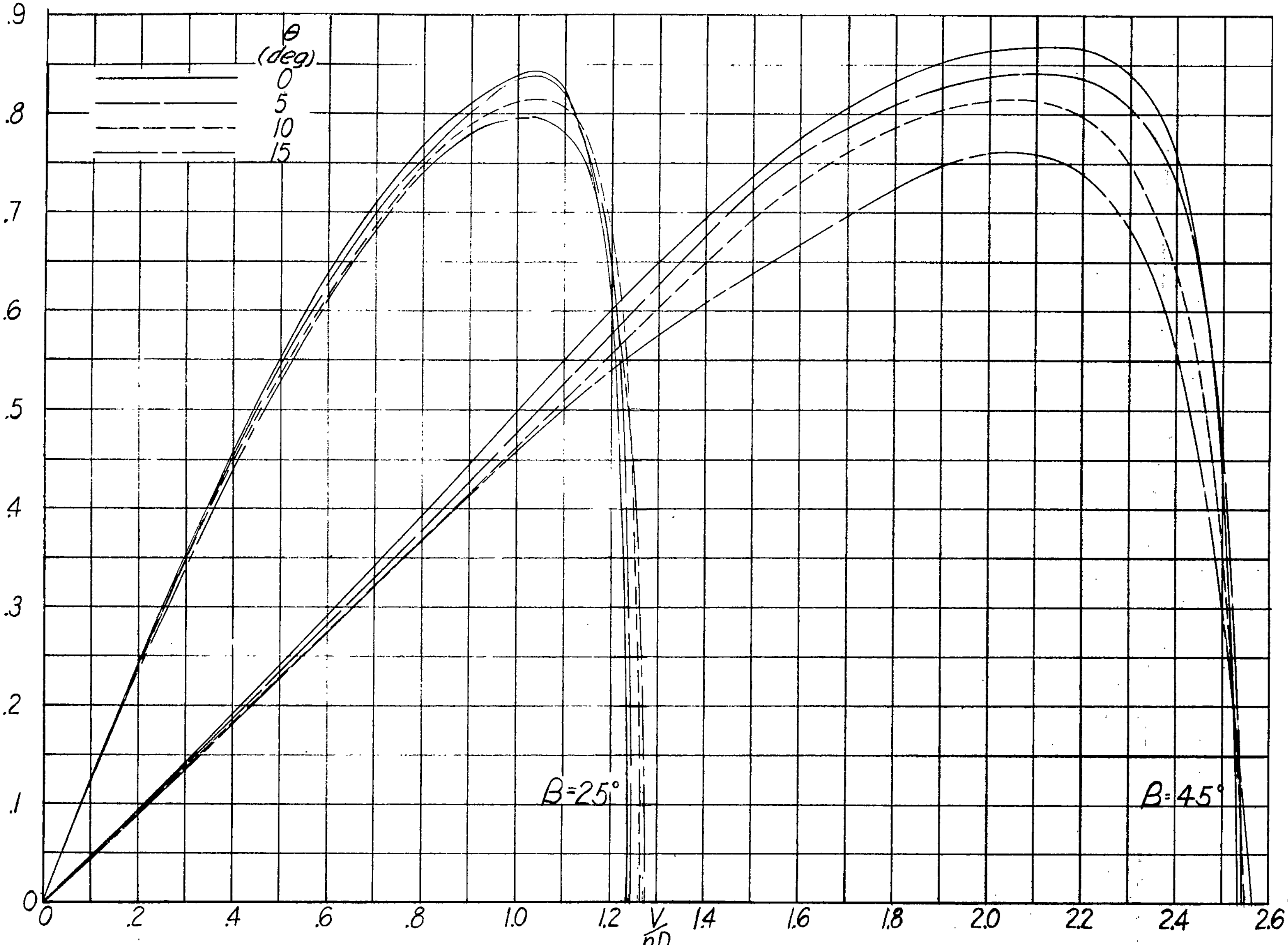


FIGURE 14.- Effect of pitch on efficiency for six-blade dual propeller.

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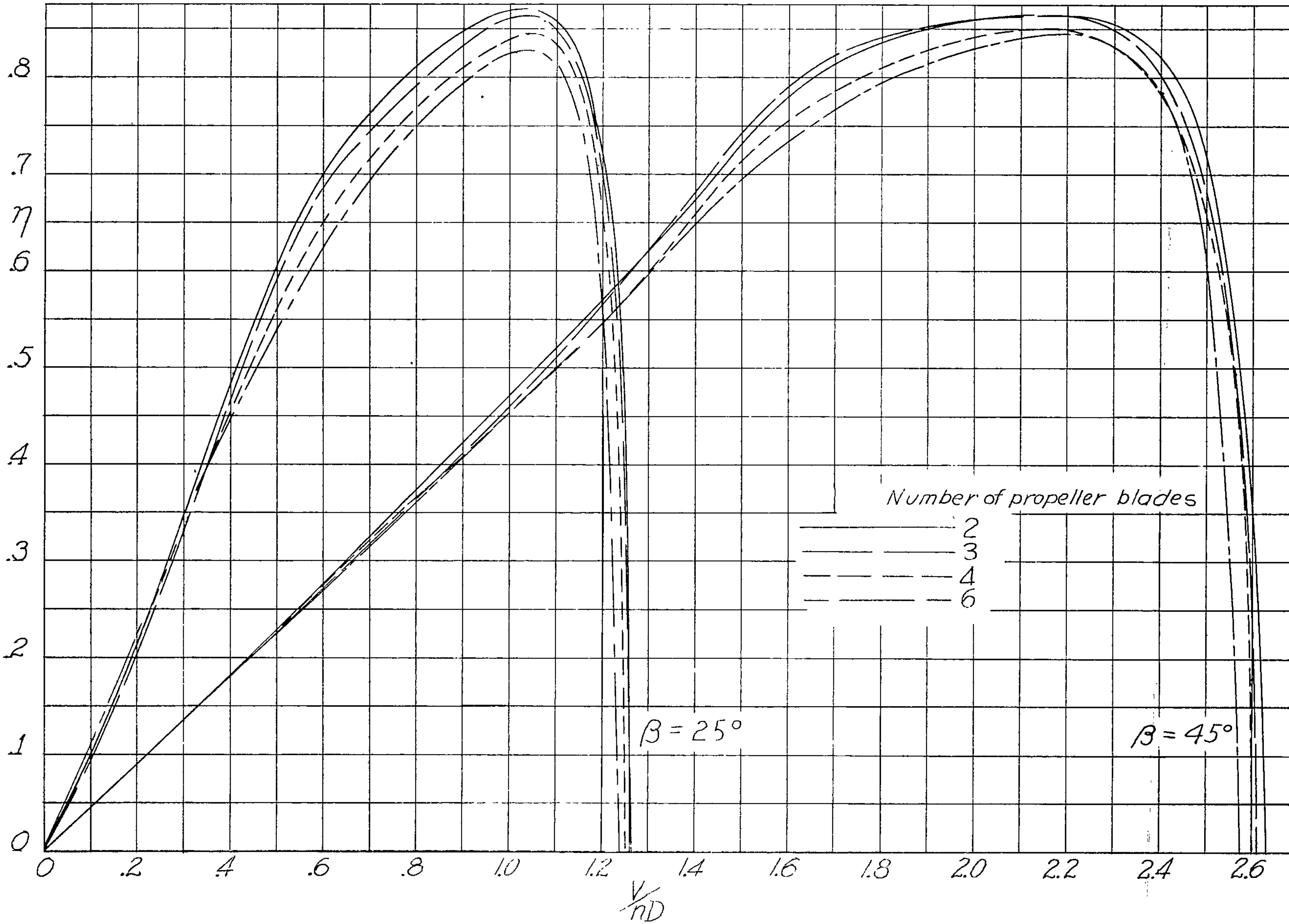
FIG. 14



NACA Fig. 15

FIGURE 15.- Effect of solidity on efficiency. $\theta = 0°$

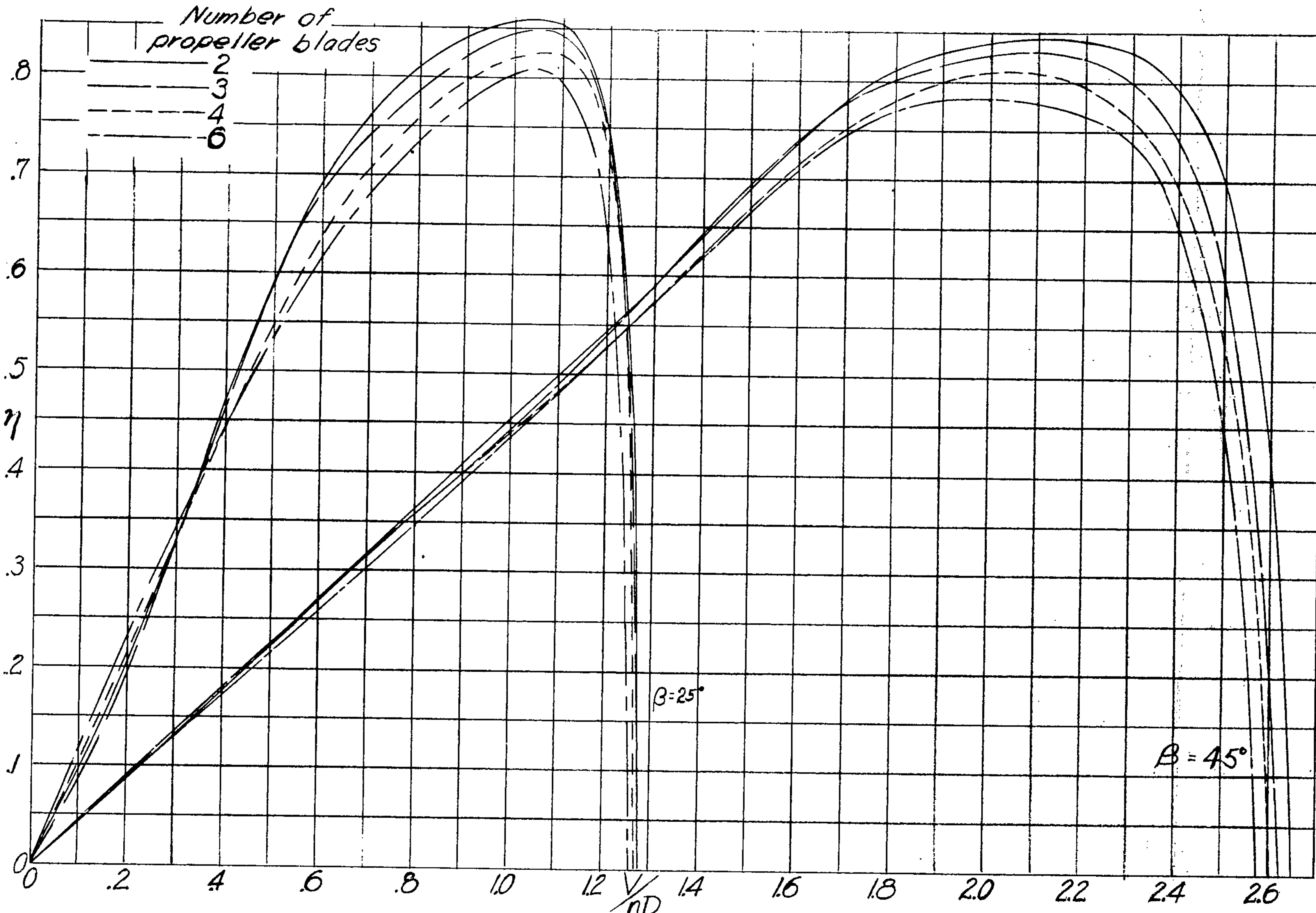


FIGURE 16. - Effect of solidity on efficiency, θ=10°.

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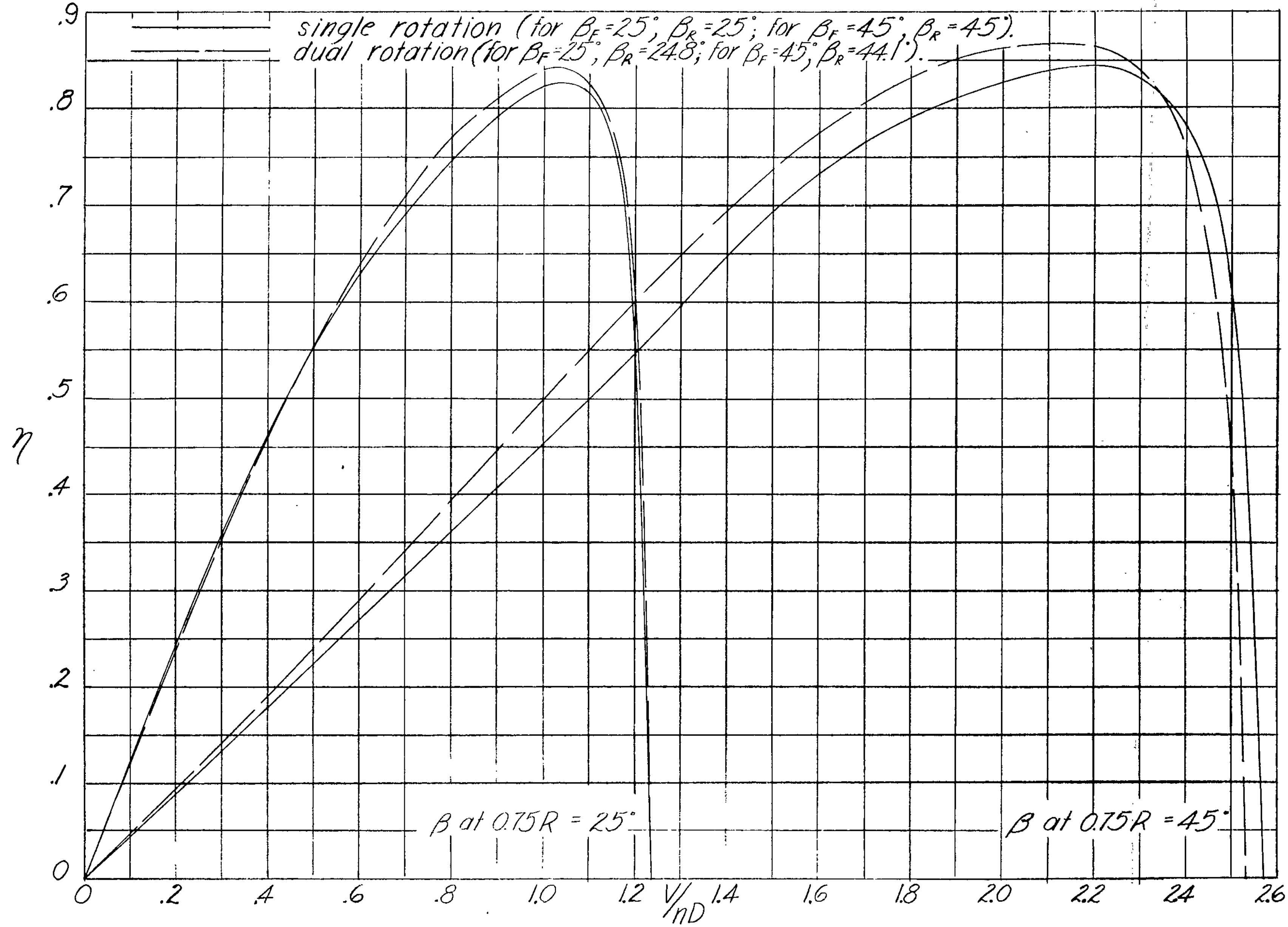

FIGURE 17.- Effect of dual rotation on efficiency. $\theta = 0°$.

Fig. 17

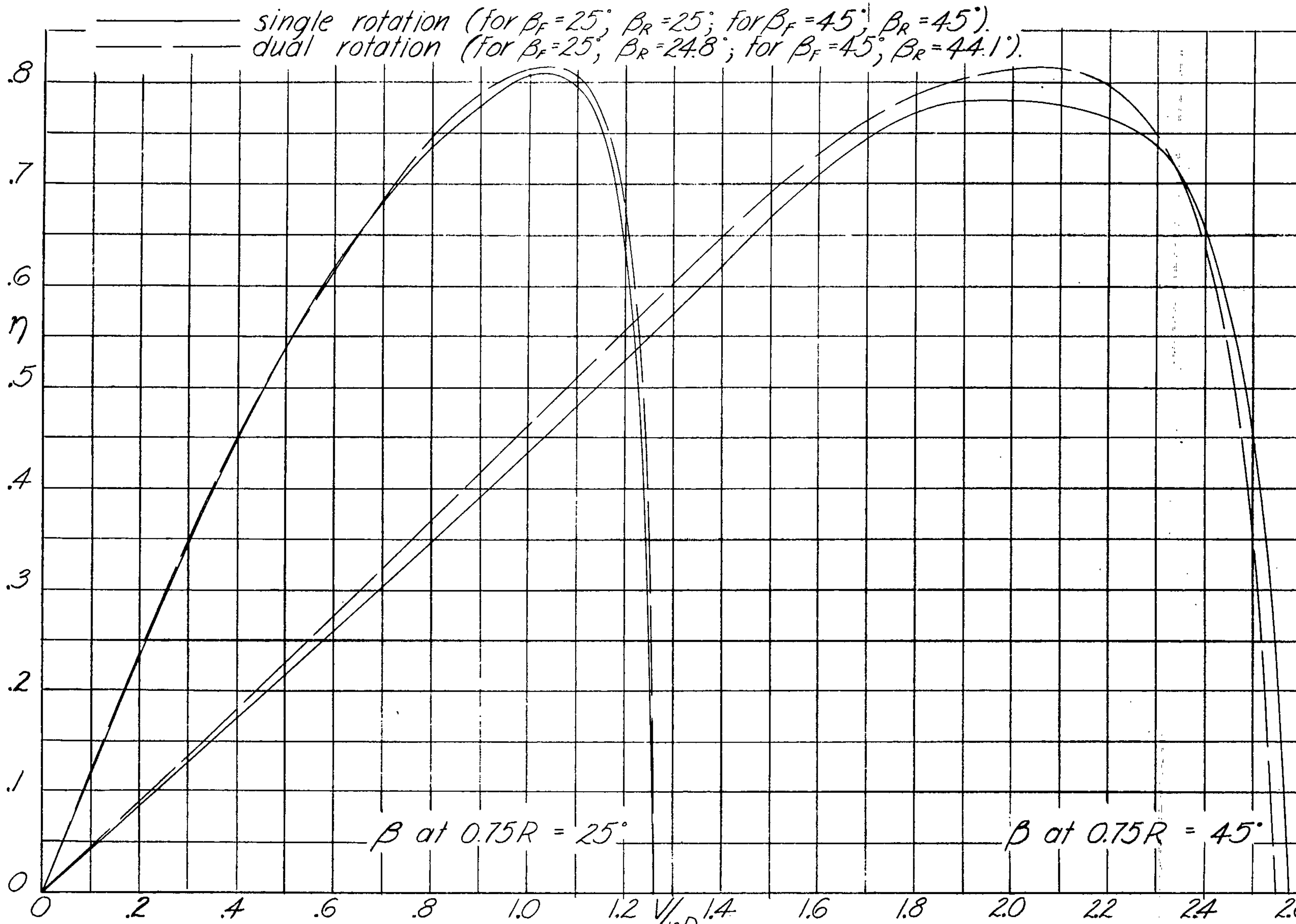

FIGURE 18.- Effect of dual rotation on efficiency. $\theta = 10°$.

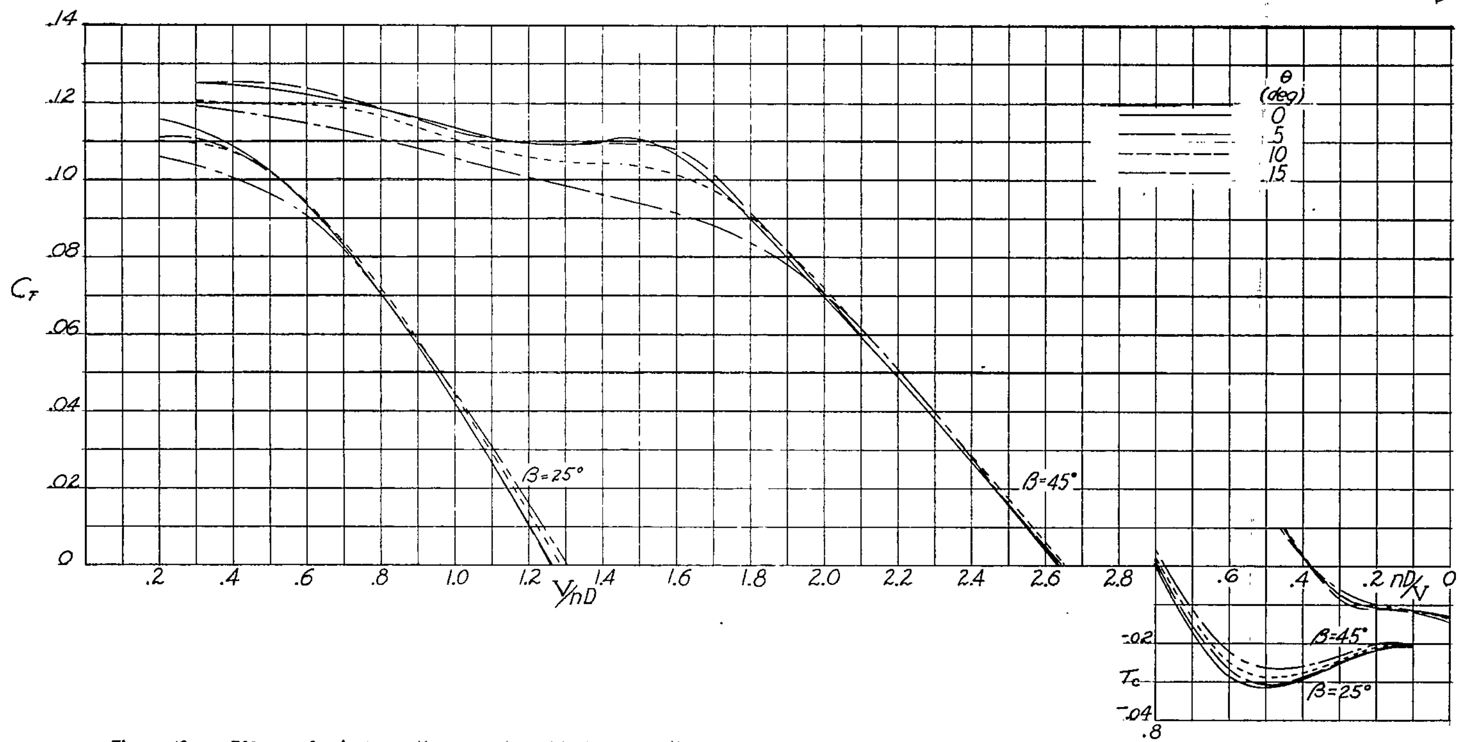

Figure 19.- Effect of pitch on thrust for two-blade propeller.

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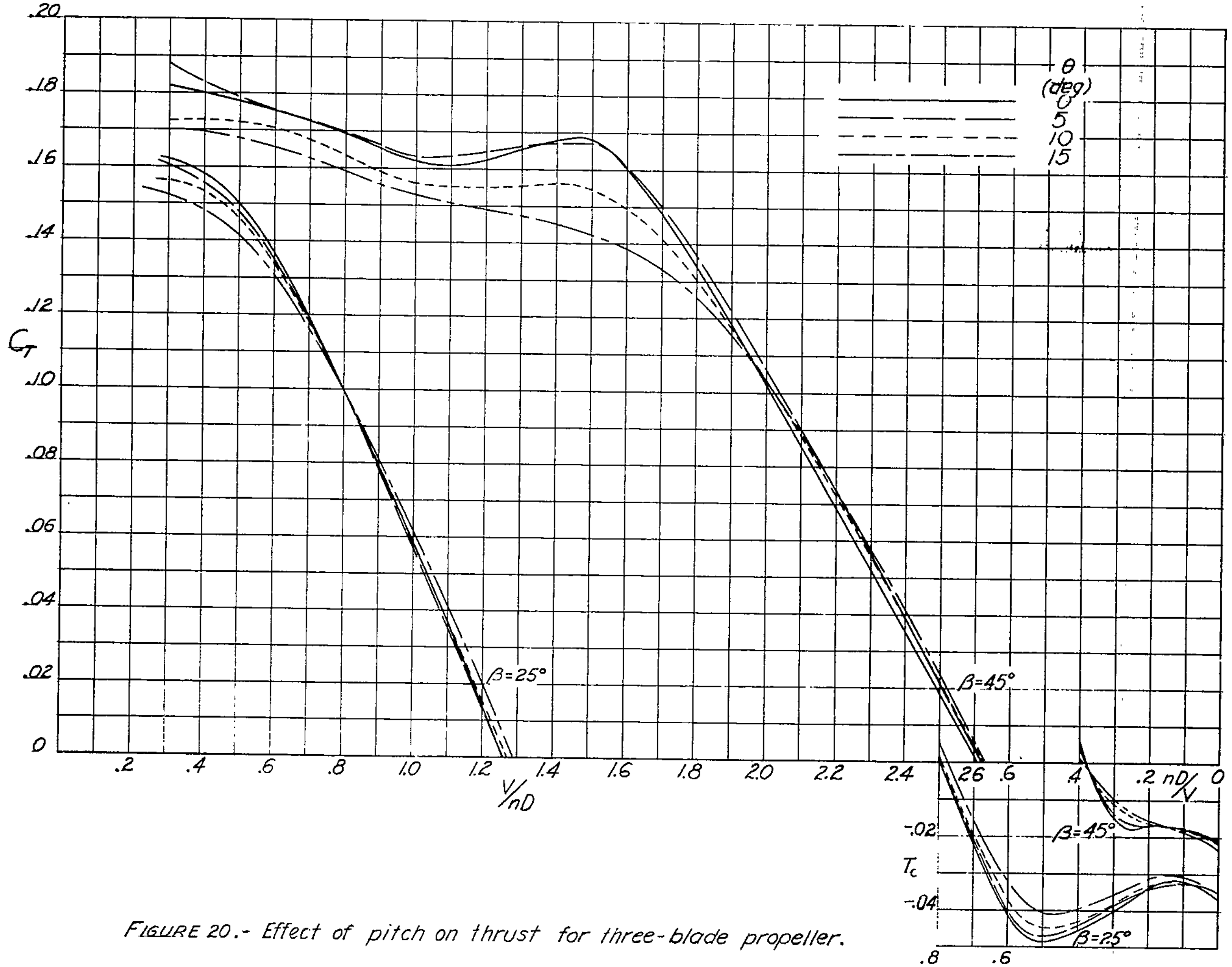


FIGURE 20.- Effect of pitch on thrust for three-blade propeller.

Fig. 20

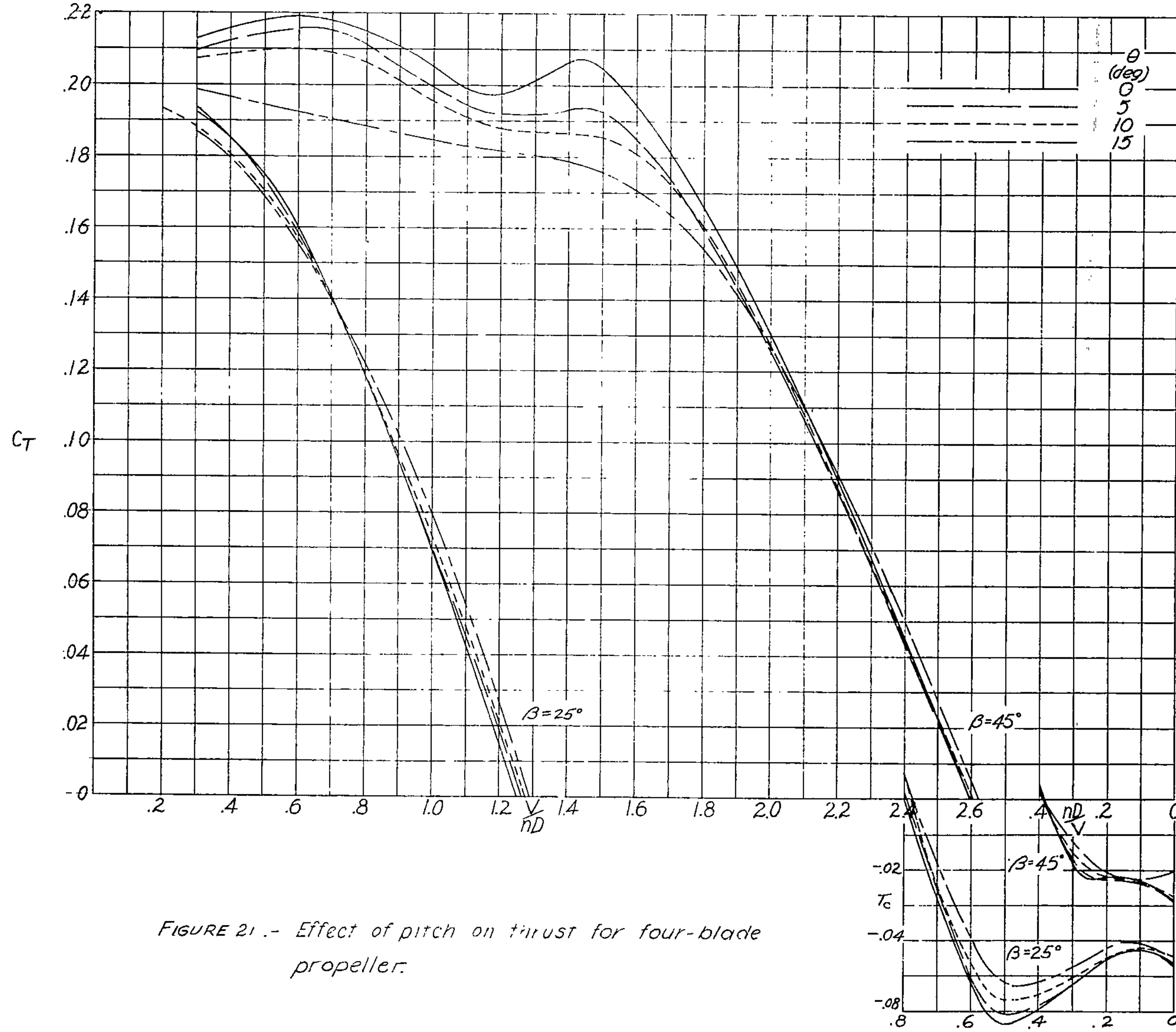


FIGURE 21.- Effect of pitch on thrust for four-blade propeller.

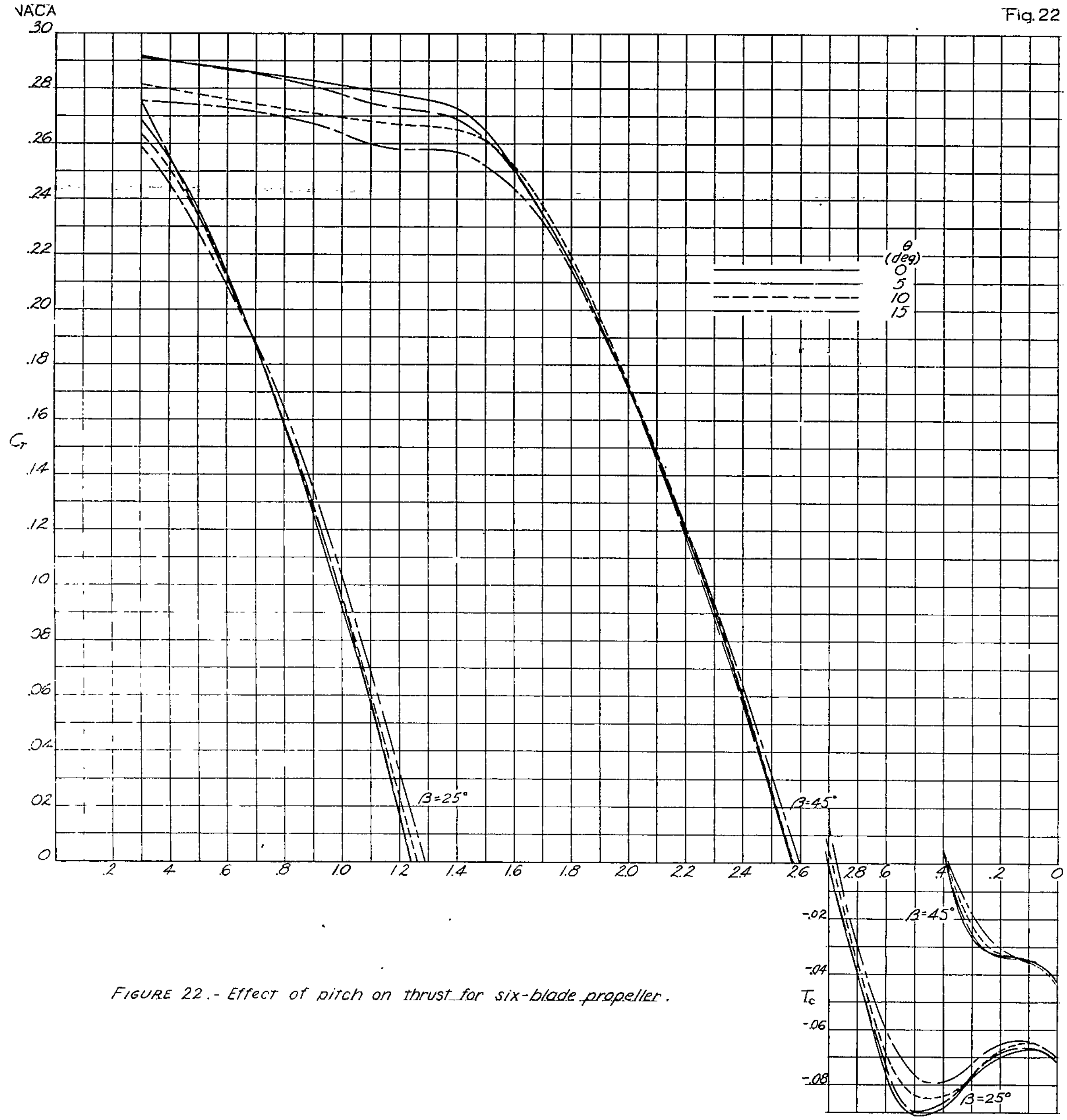


FIGURE 22.- Effect of pitch on thrust for six-blade propeller.

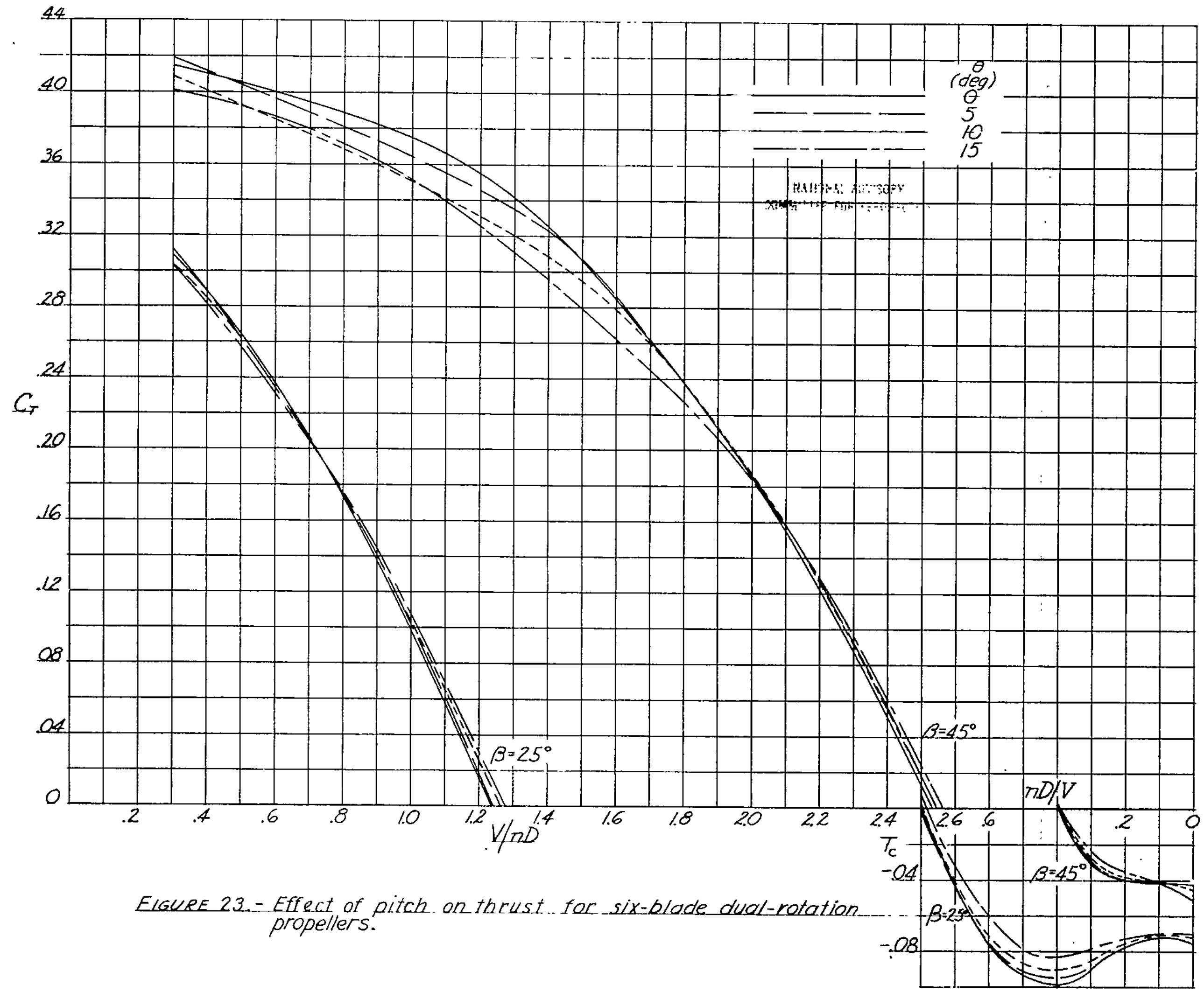


FIGURE 23.- Effect of pitch on thrust for six-blade dual-rotation propellers.

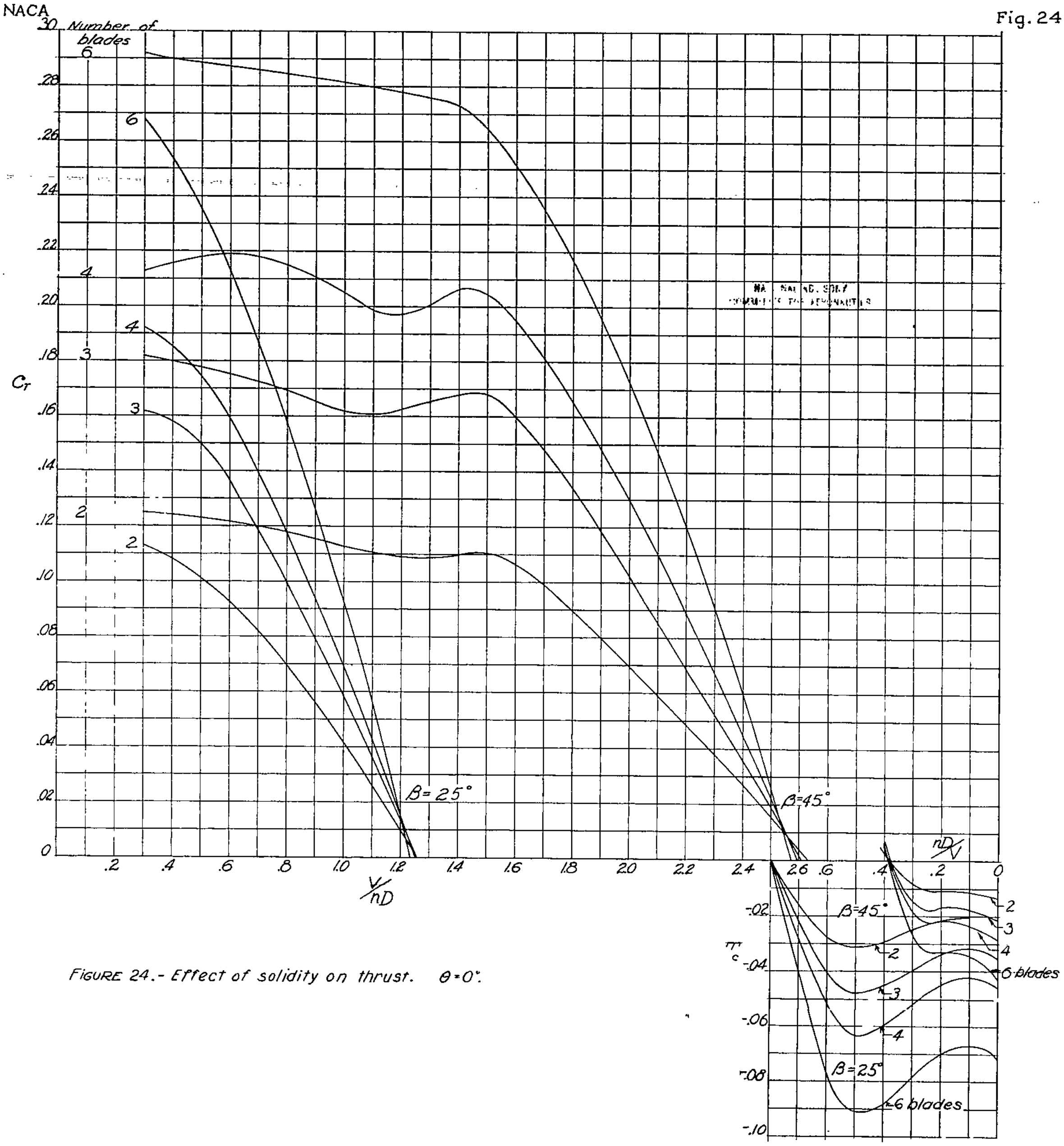


FIGURE 24.- Effect of solidity on thrust. $\theta = 0°$.

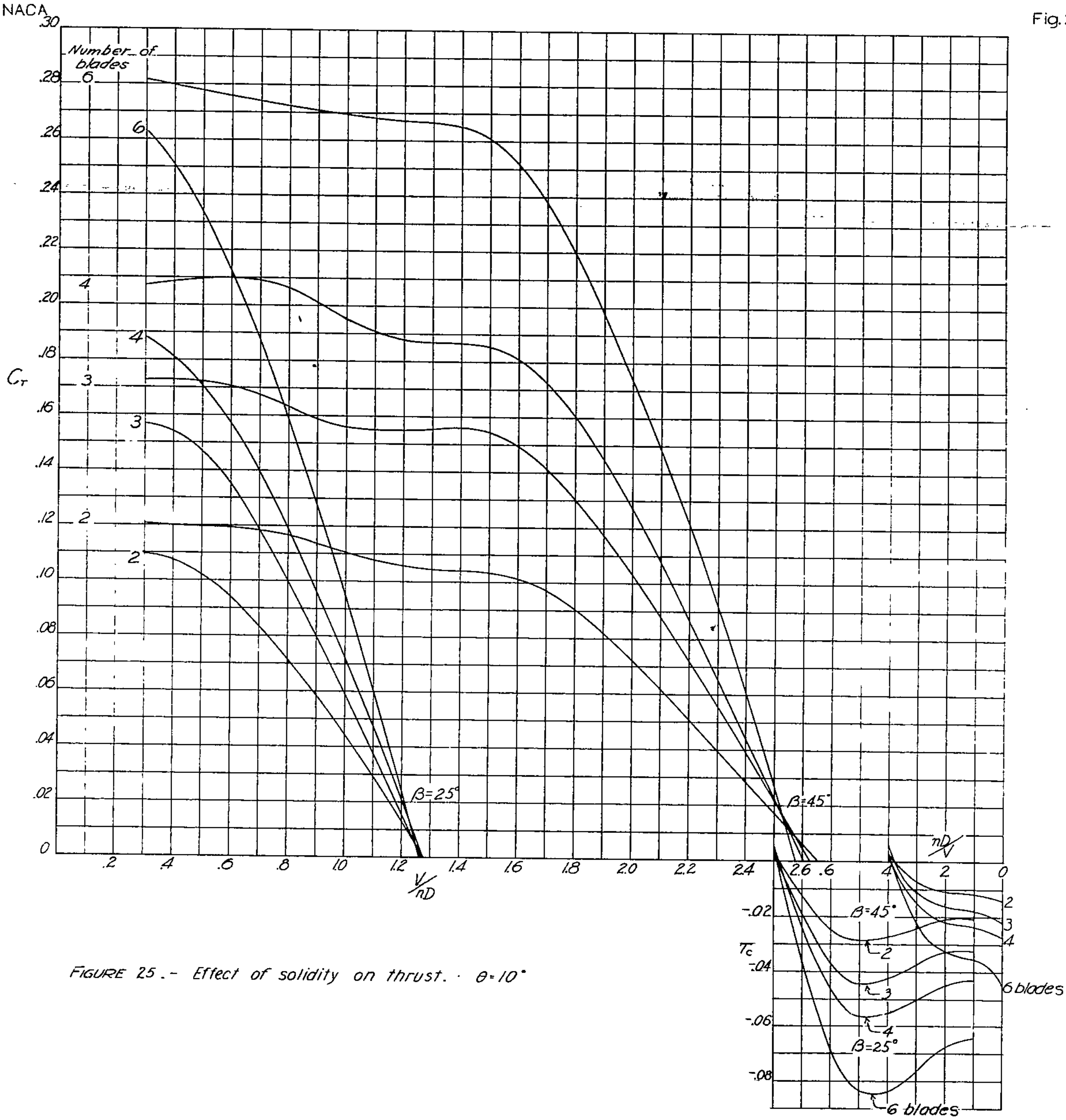


FIGURE 25.- Effect of solidity on thrust. · θ=10°

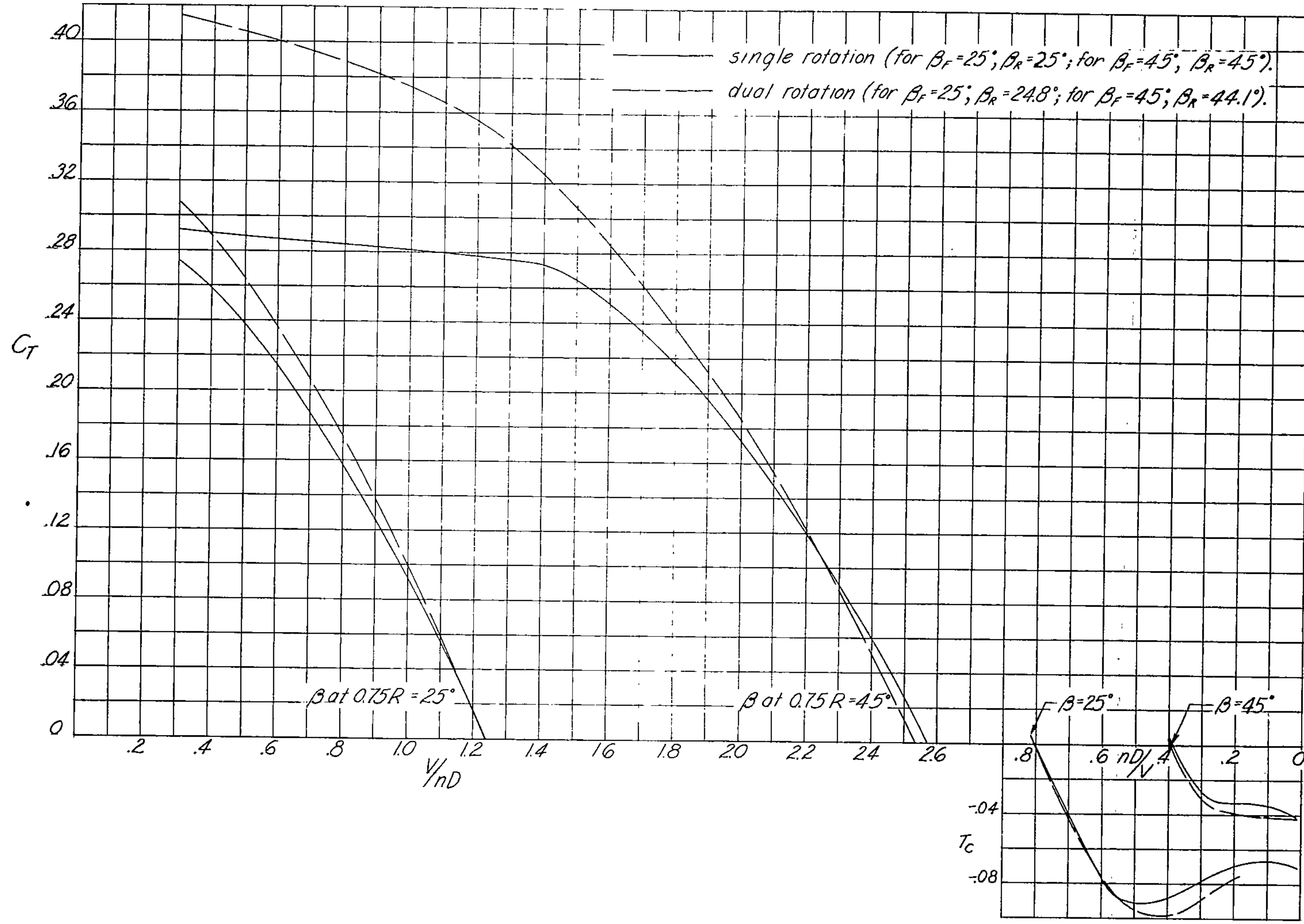


FIGURE 26.- Effect of dual rotation on thrust. $\theta = 0°$.

NACA

Fig. 26

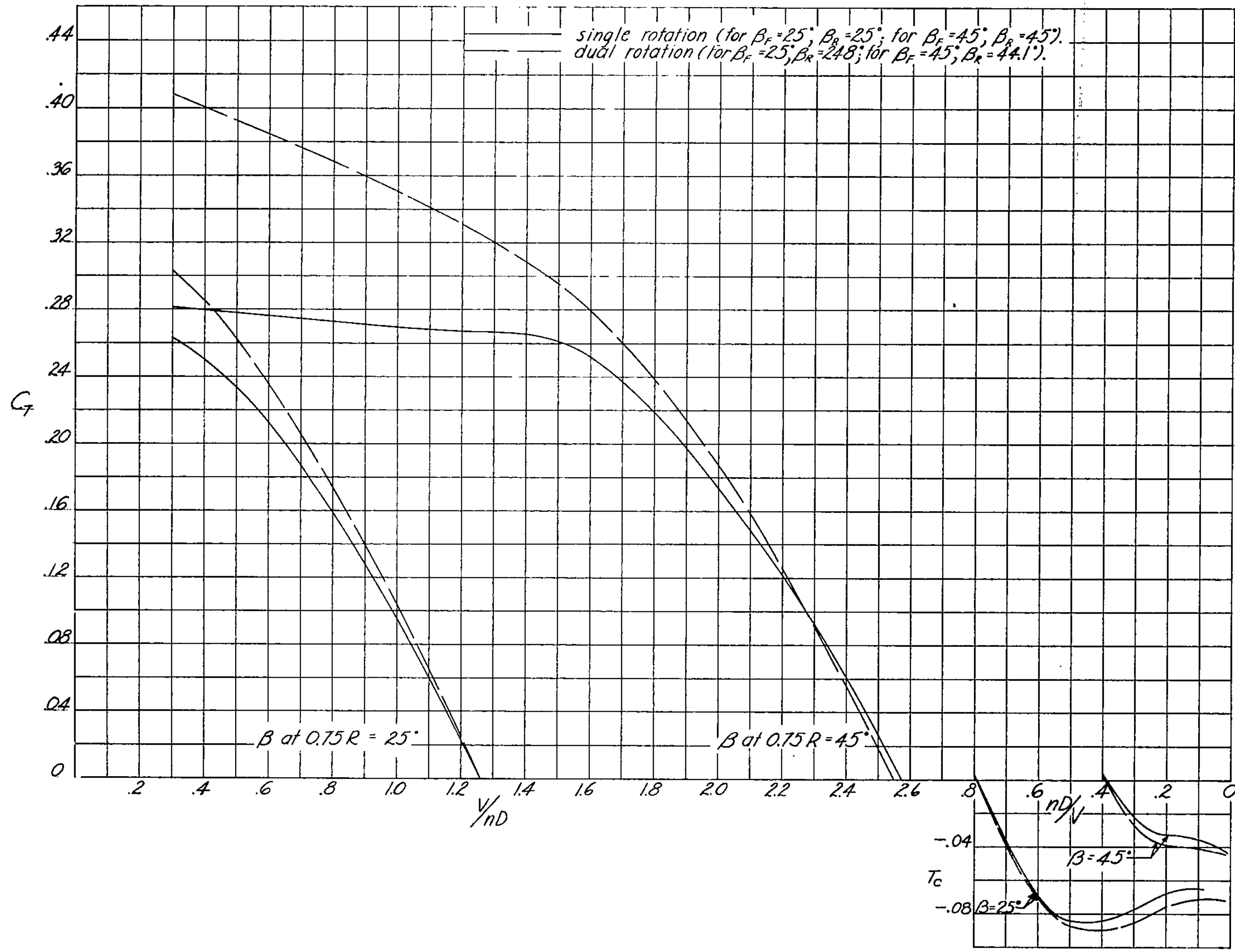


FIGURE 27.- Effect of dual rotation on thrust. θ=10°

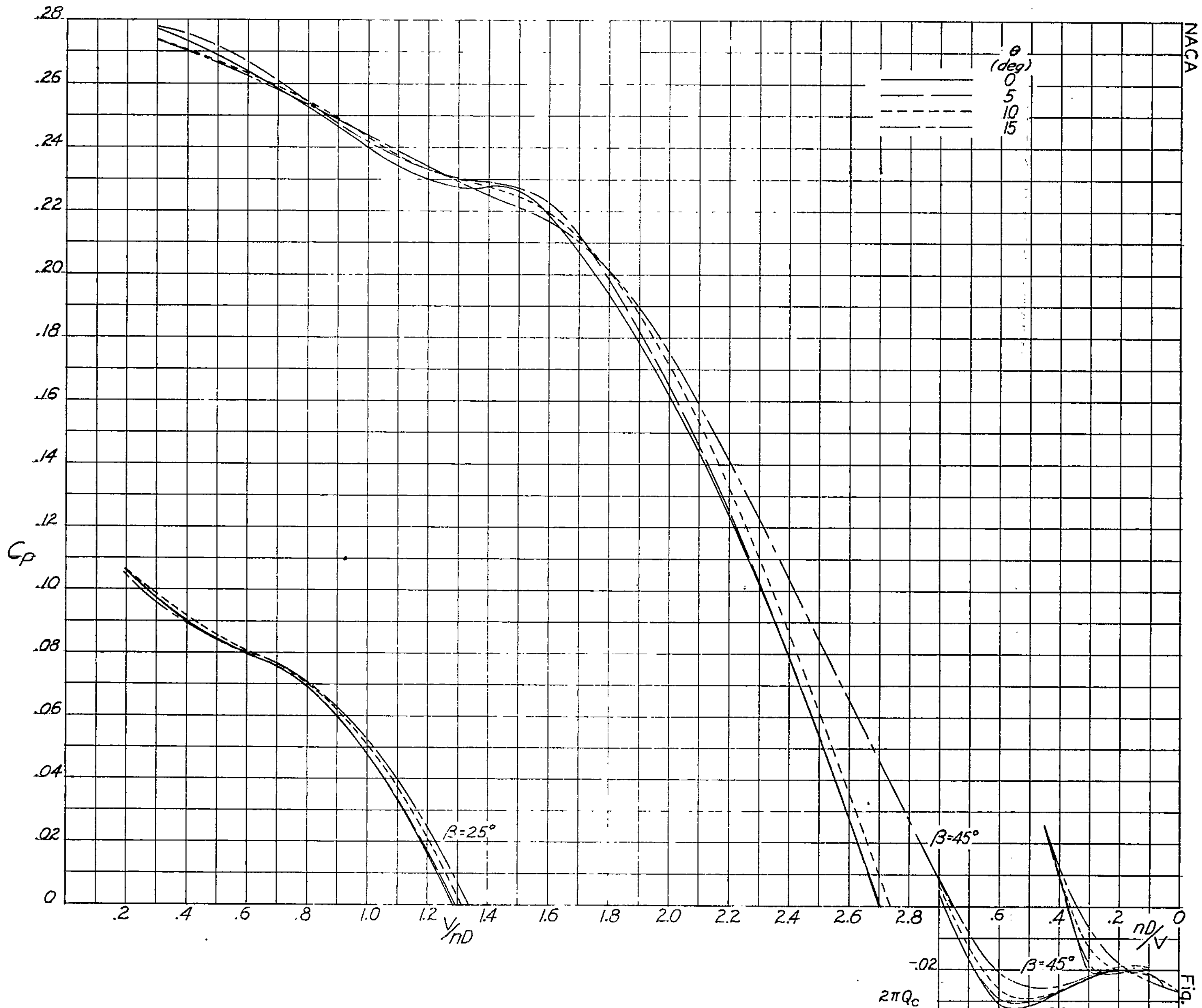


FIGURE 28.-Effect of pitch on power for two-blade propeller

Fig. 28

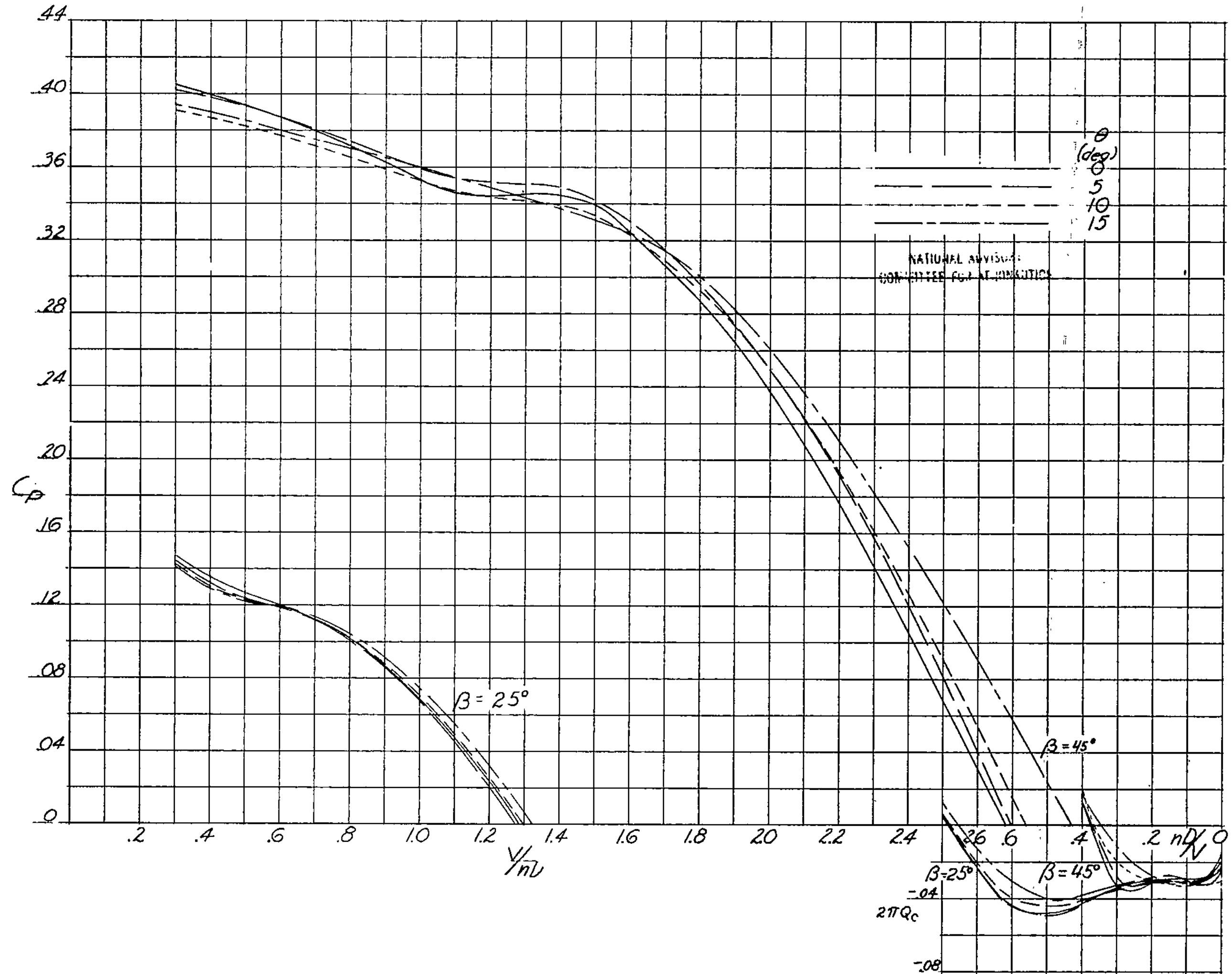


FIGURE 29.- Effect of pitch on power for three-blade propeller.

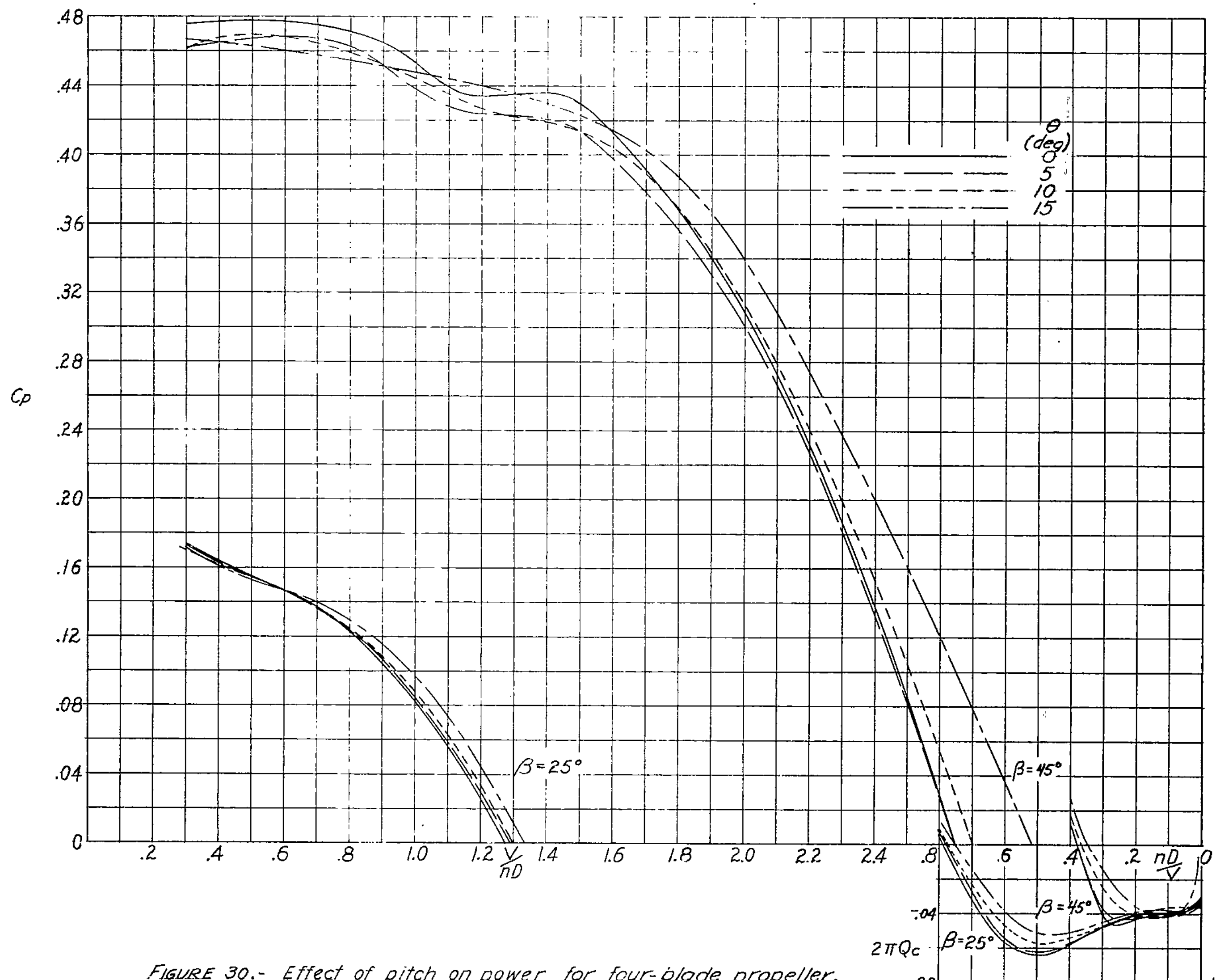


FIGURE 30.- Effect of pitch on power for four-blade propeller.

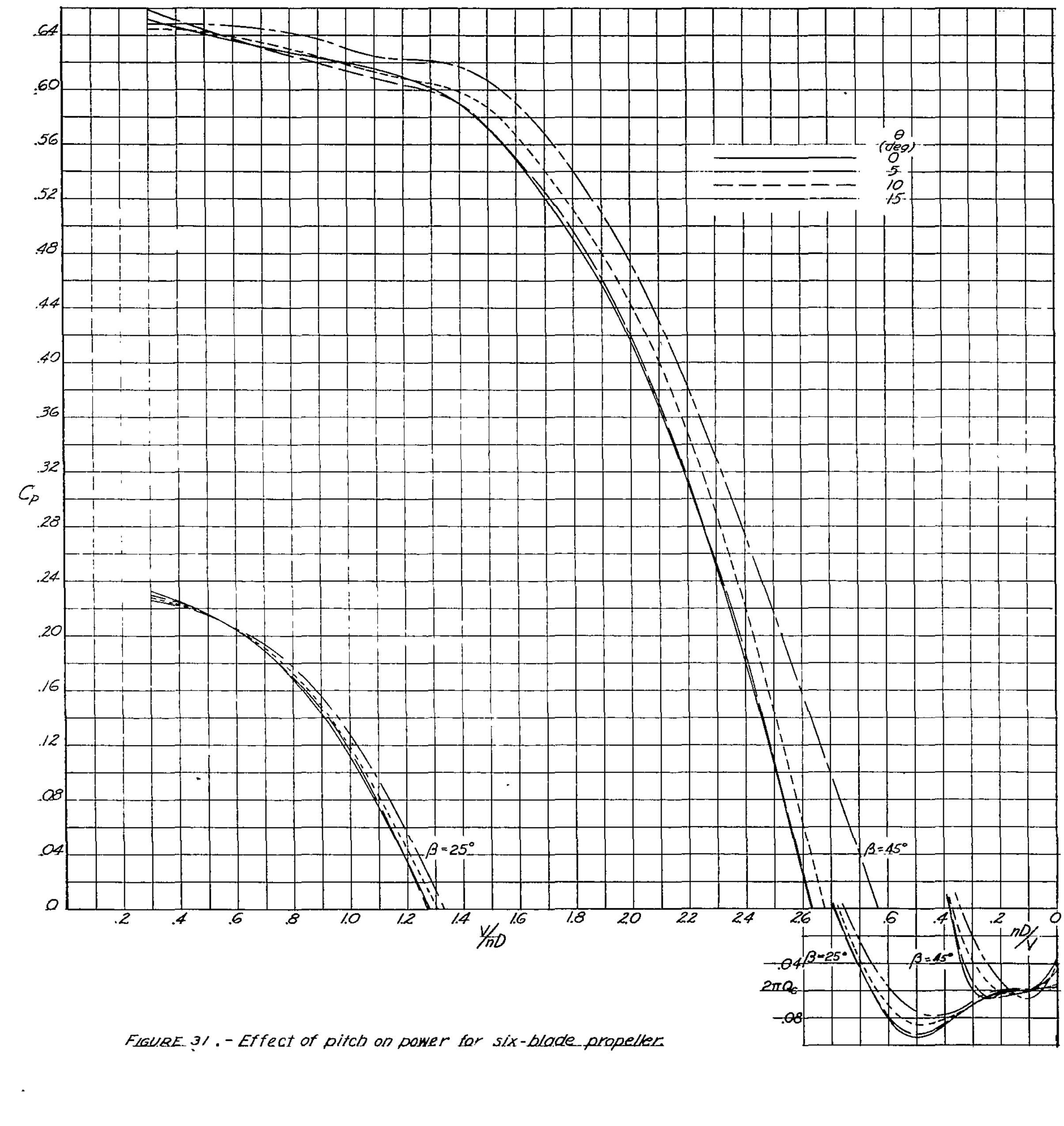


FIGURE 31. - Effect of pitch on power for six-blade propeller.

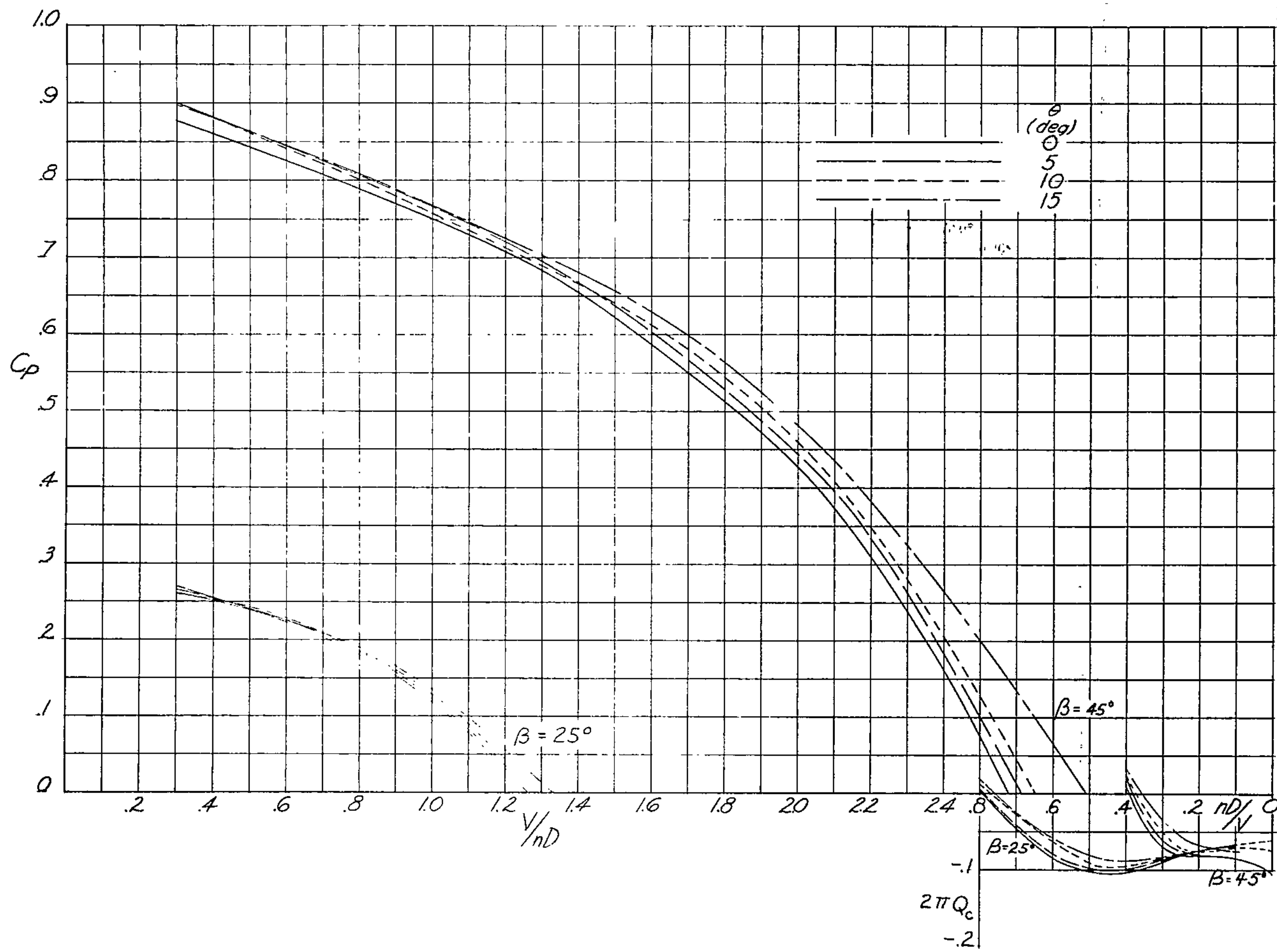


FIGURE 32.- Effect of pitch on power for six-blade dual-rotation propellers.

NACA Fig. 33

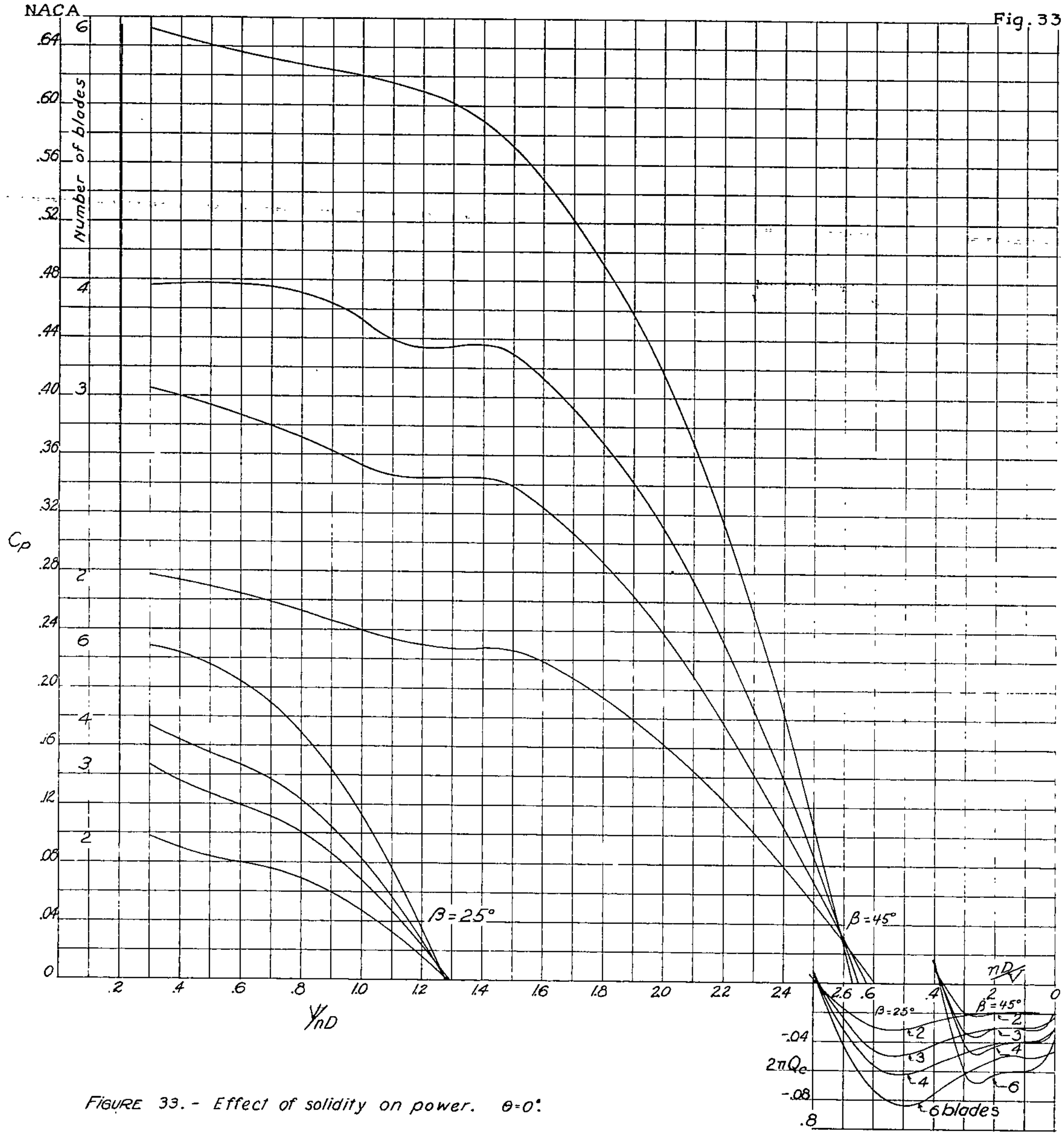


FIGURE 33.- Effect of solidity on power. θ=0°.

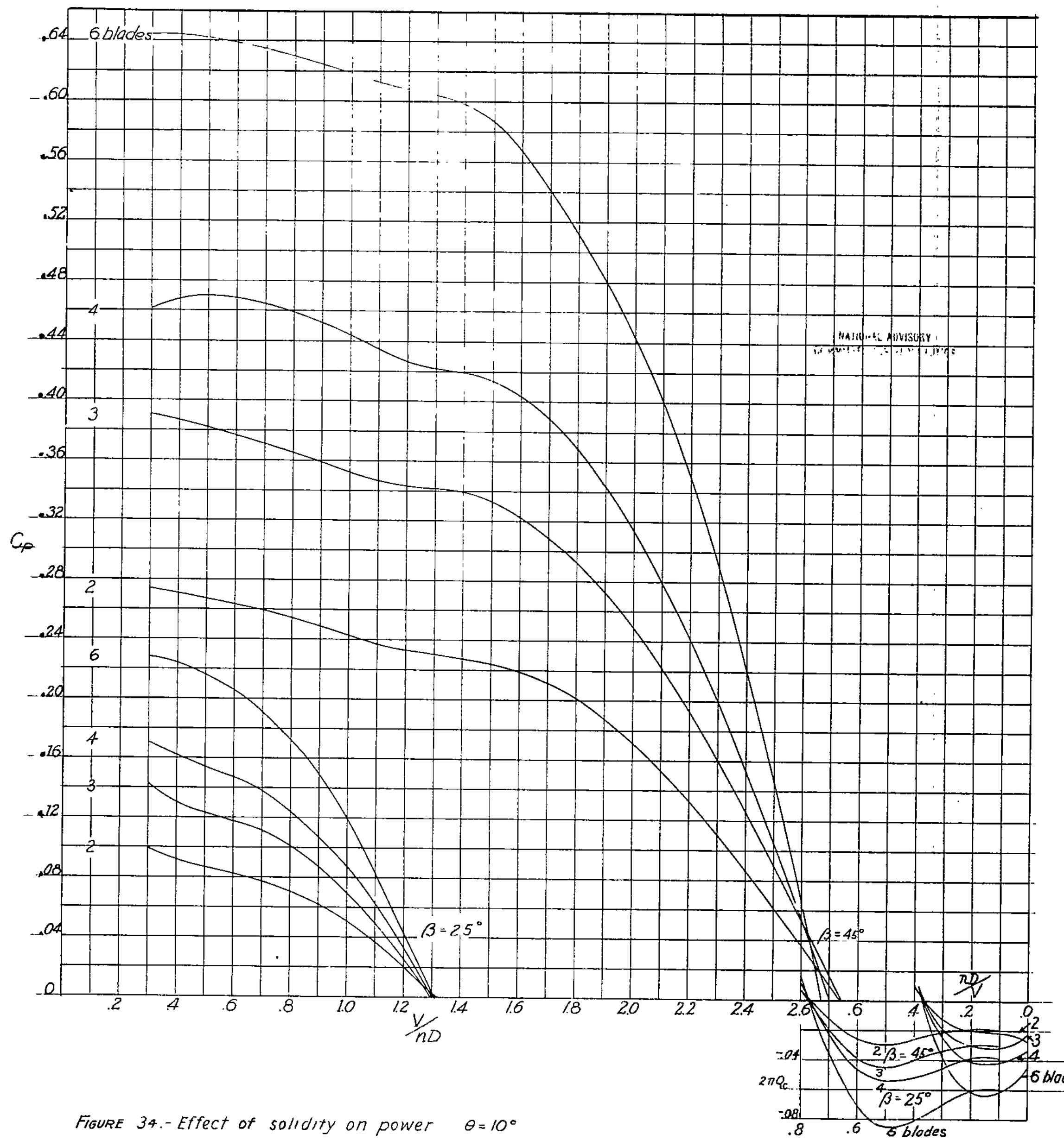


FIGURE 34.- Effect of solidity on power θ = 10°

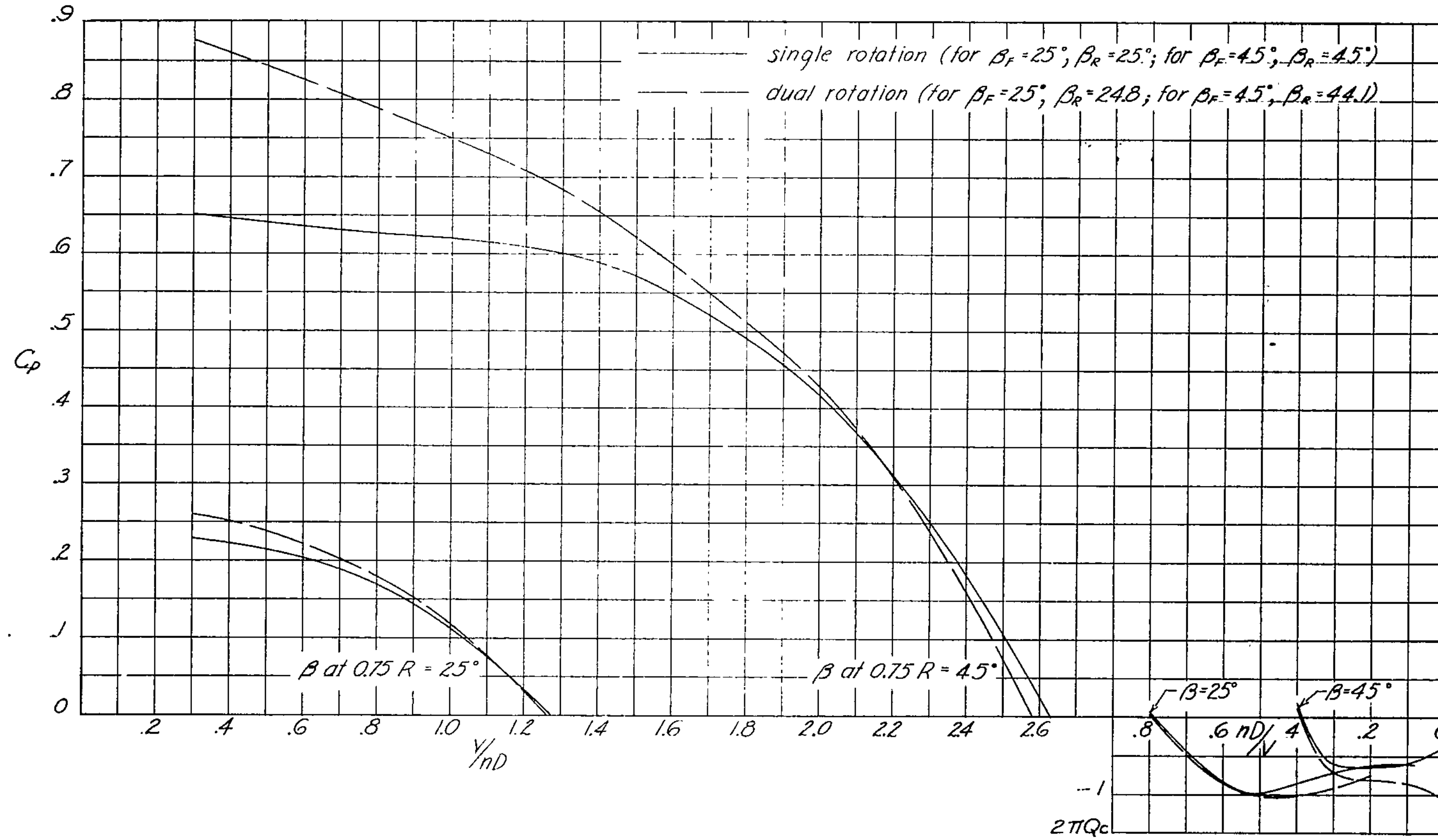


FIGURE 35.- Effect of dual rotation on power. θ=0°.

NACA

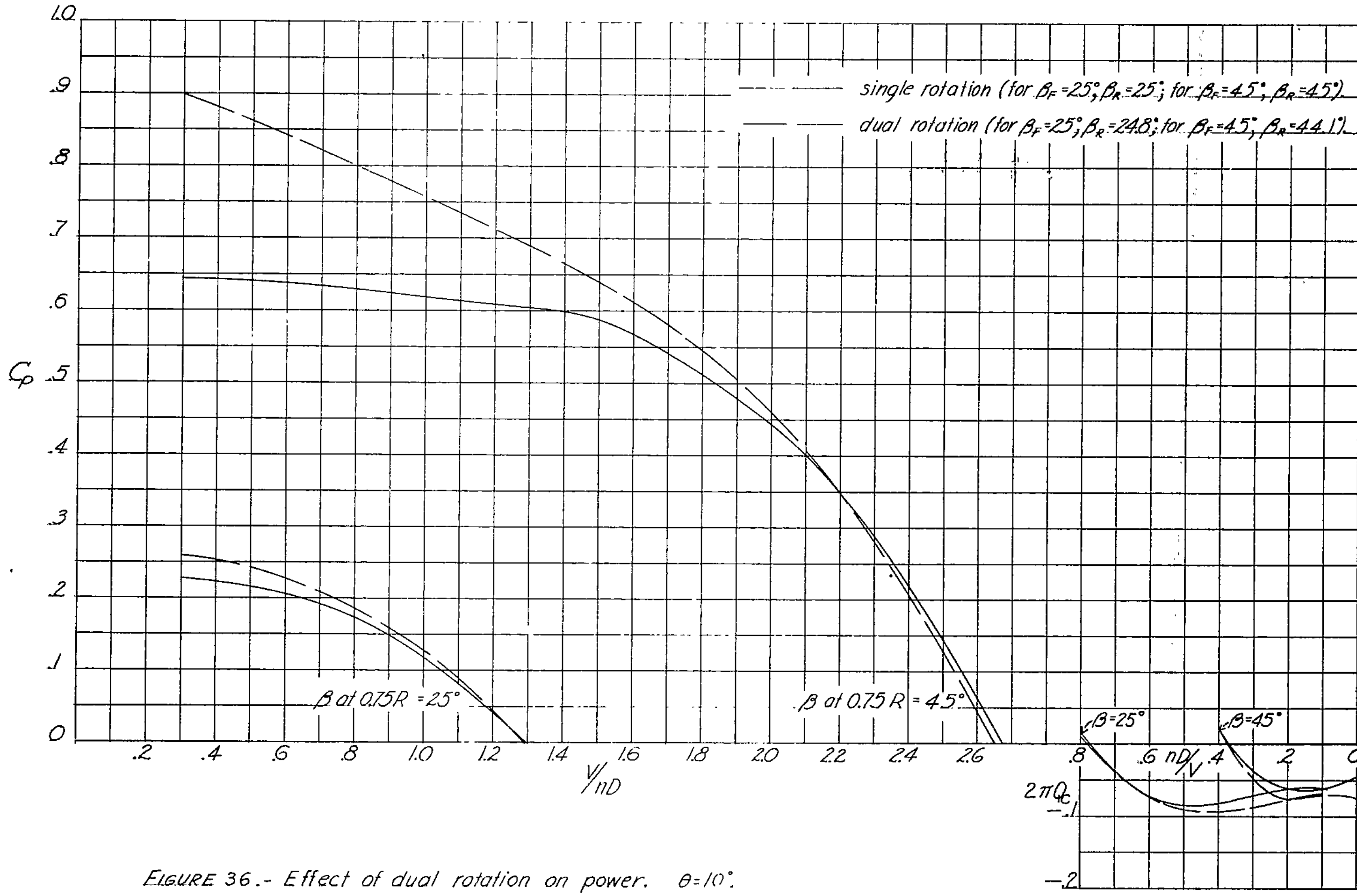


FIGURE 36.- Effect of dual rotation on power. θ=10°.

Fig. 36

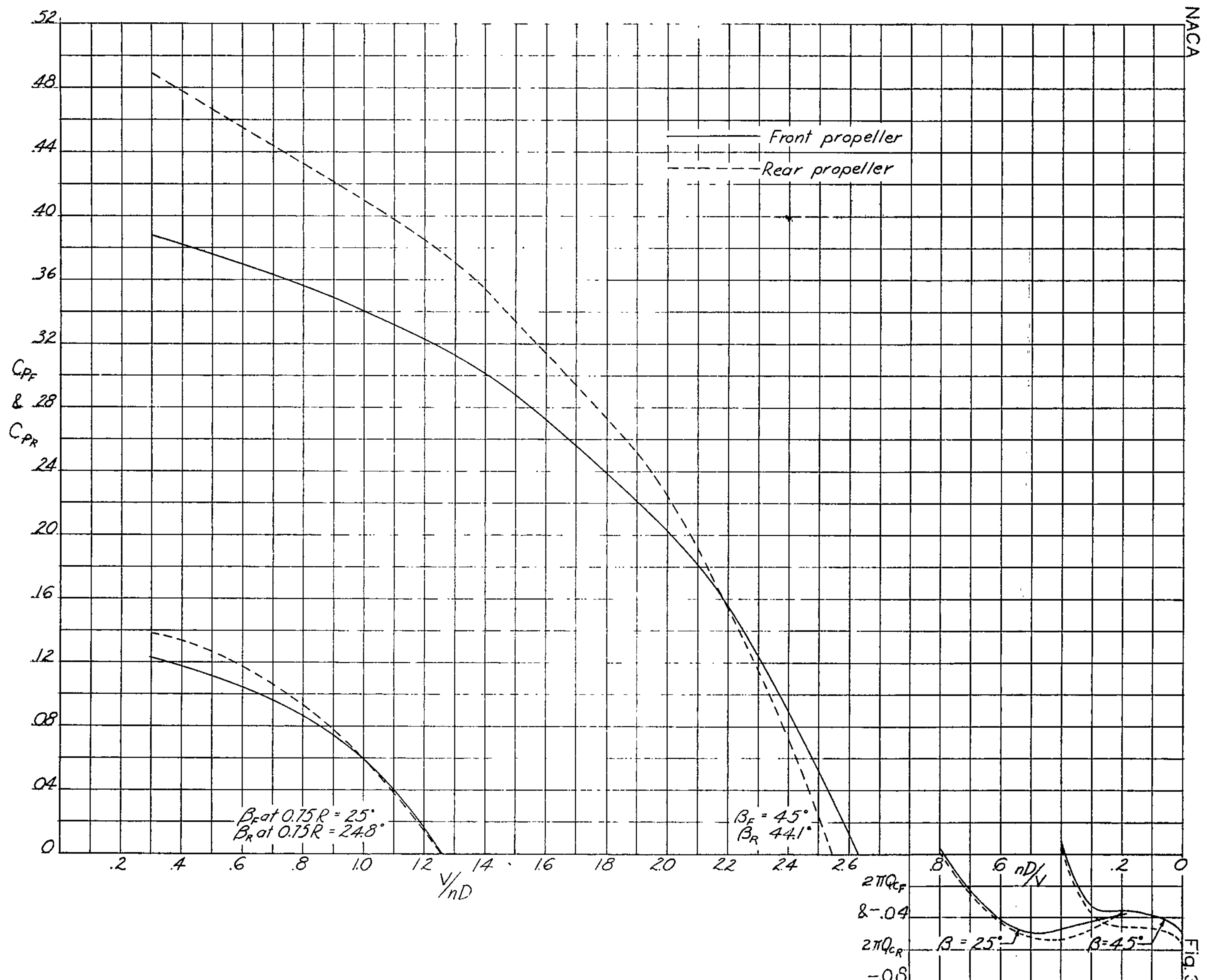


FIGURE 37.– Individual power-coefficient curves for six-blade dual-rotation propellers. $\theta = 0°$.

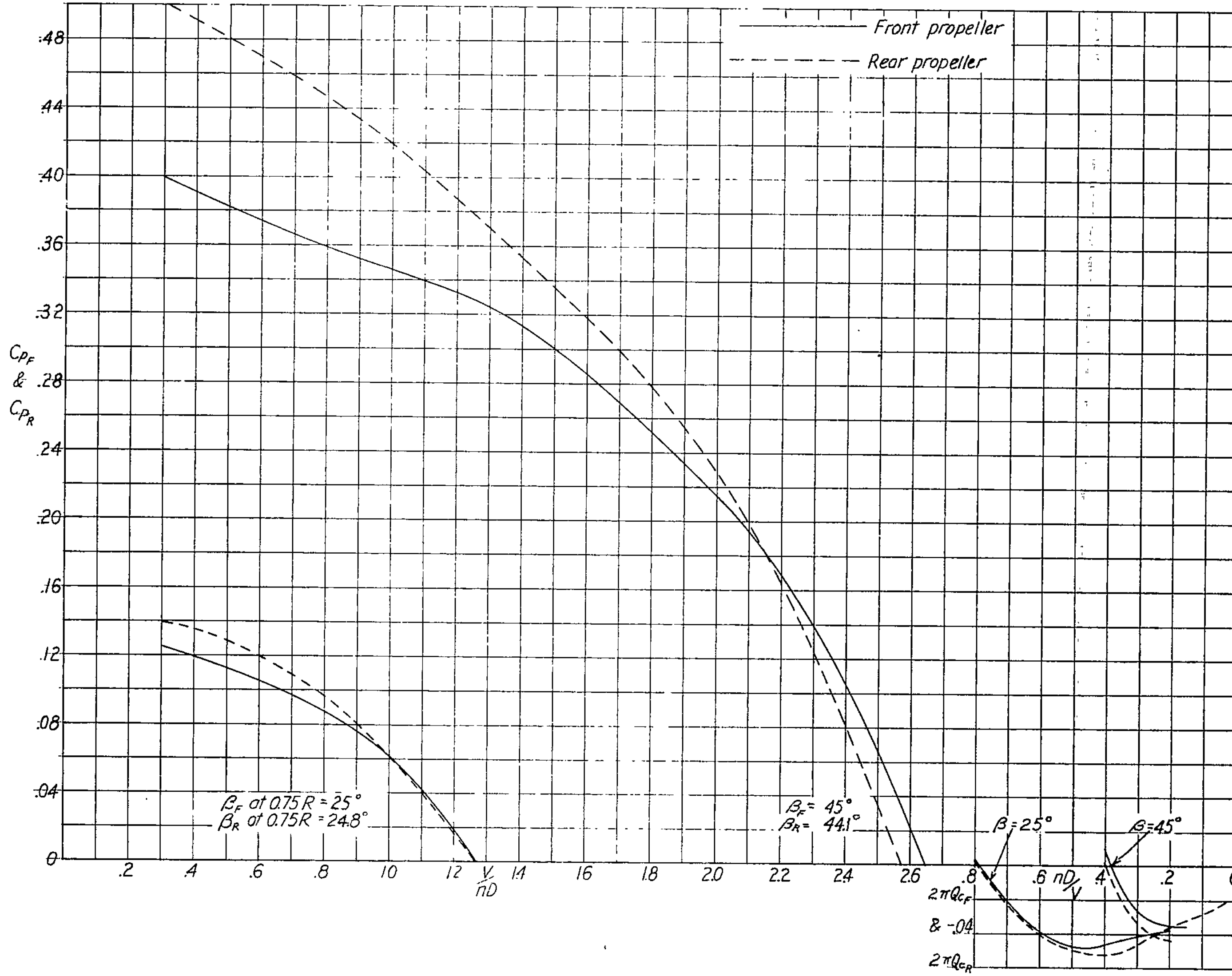


FIGURE 38.- Individual power coefficient curves for six-blade dual-rotation propellers. $\theta = 5°$

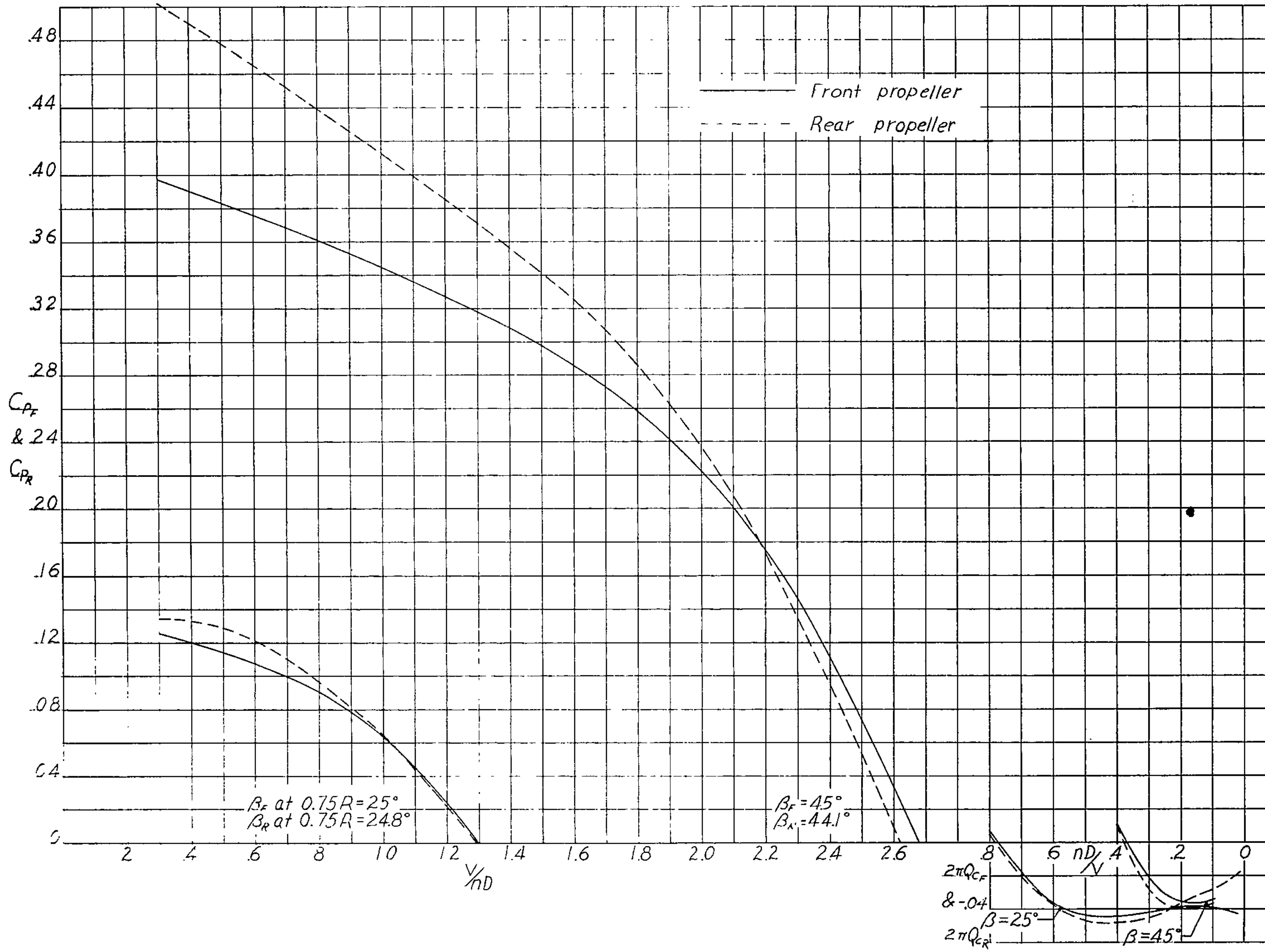


Figure 39.- Individual power-coefficient curves for six-blade dual-rotation propellers. θ=10°.

NACA

Fig. 39

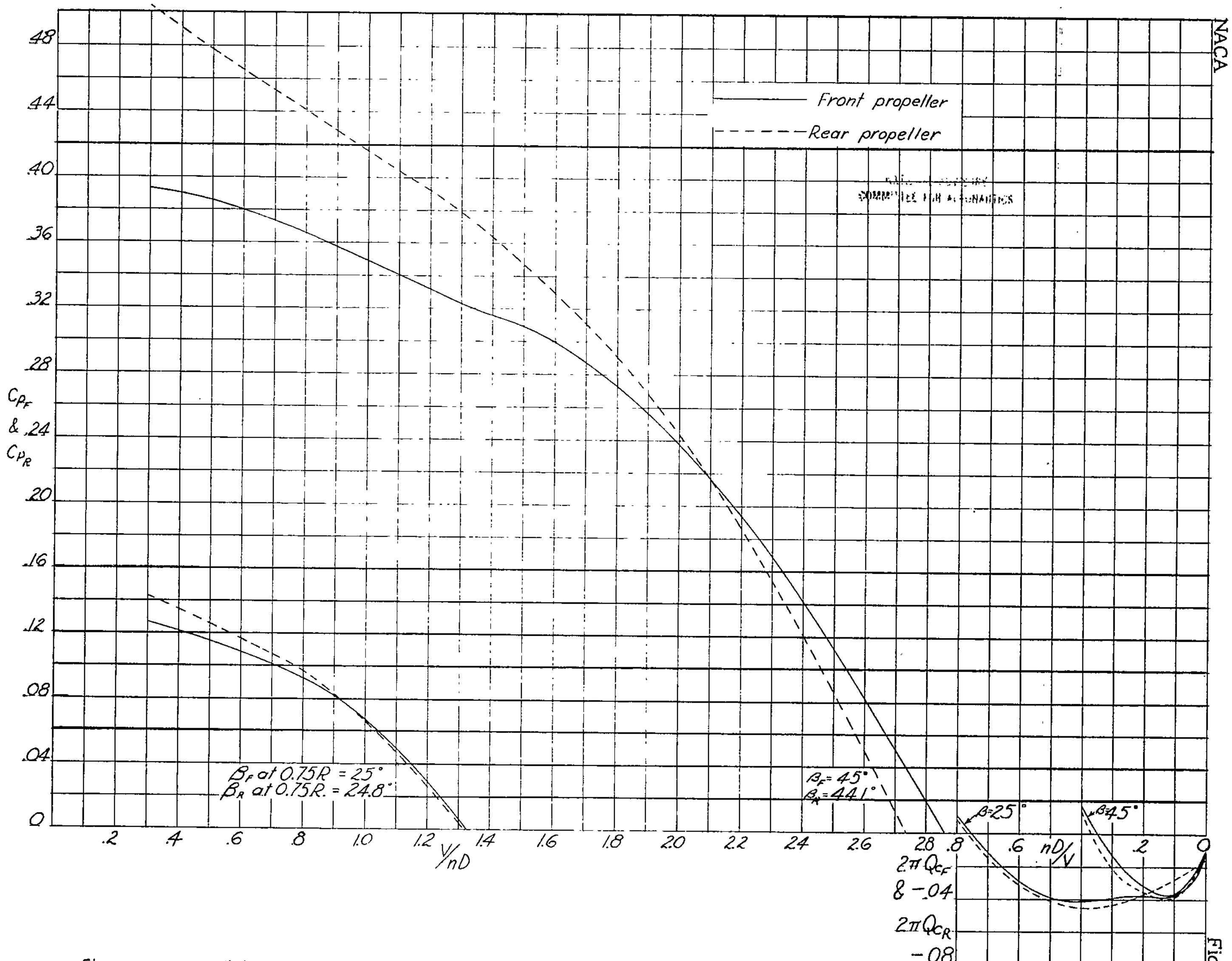
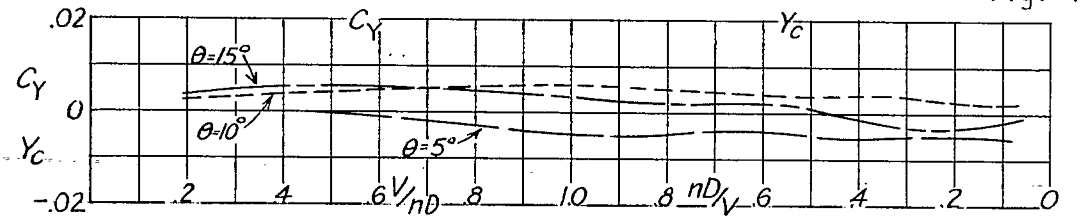
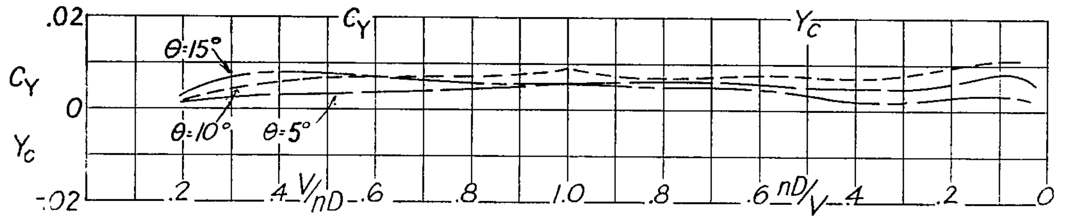


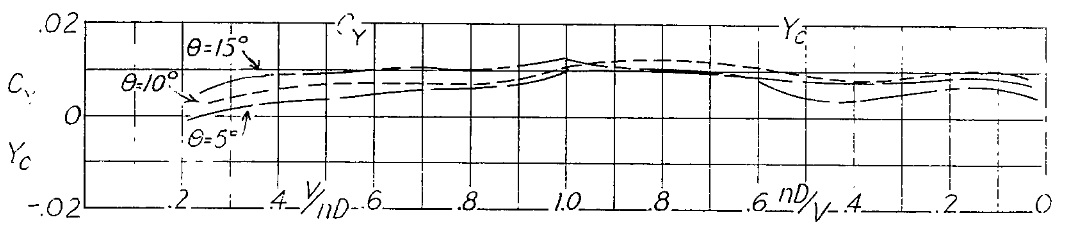
FIGURE 40.- Individual power-coefficient curves for six-blade dual-rotation propellers. $\theta = 15°$.



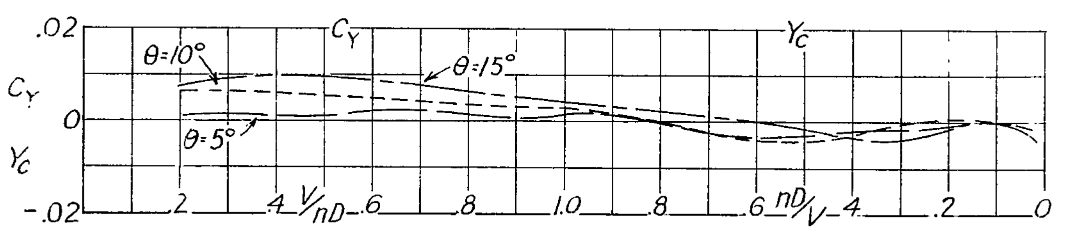
(a) Two-blade propeller



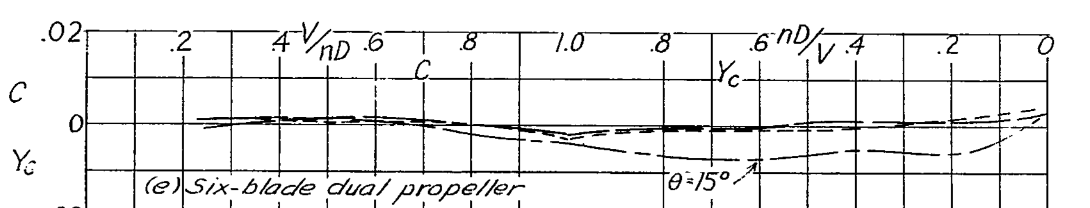
(b) Three-blade propeller



(c) Four-blade propeller



(d) Six-blade propeller



(e) Six-blade dual propeller

FIGURE 41.– Effect of pitch on side force β=25°

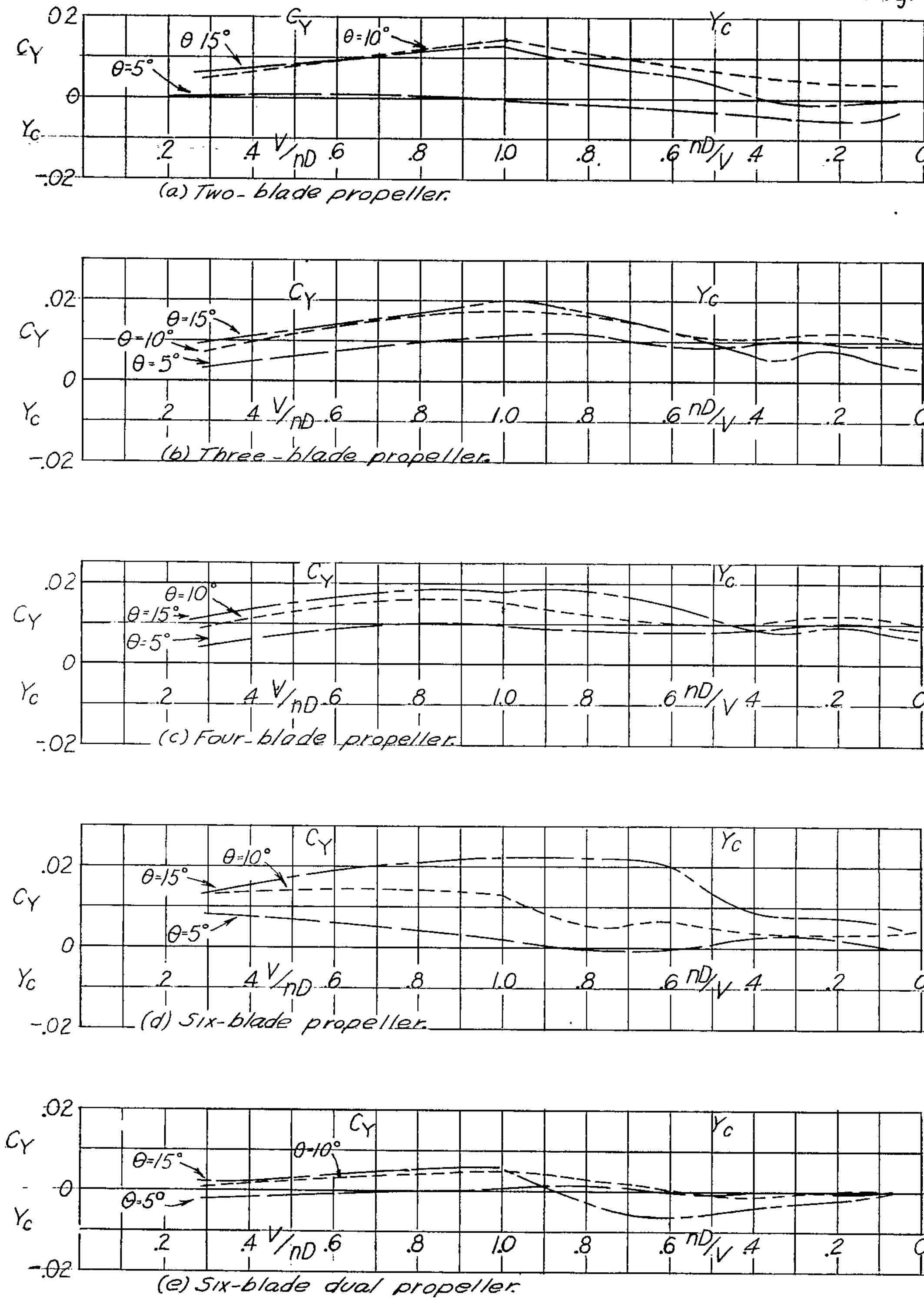
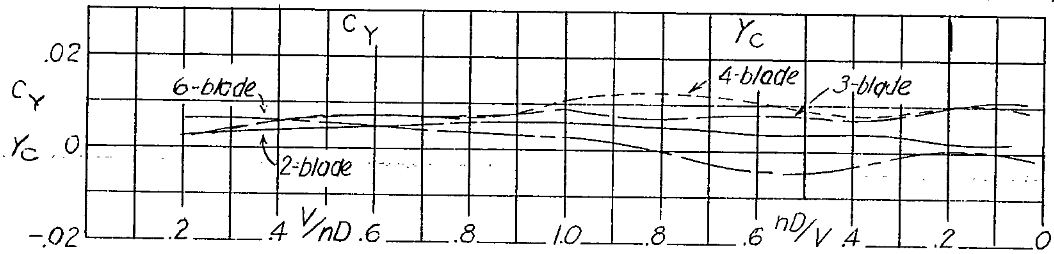
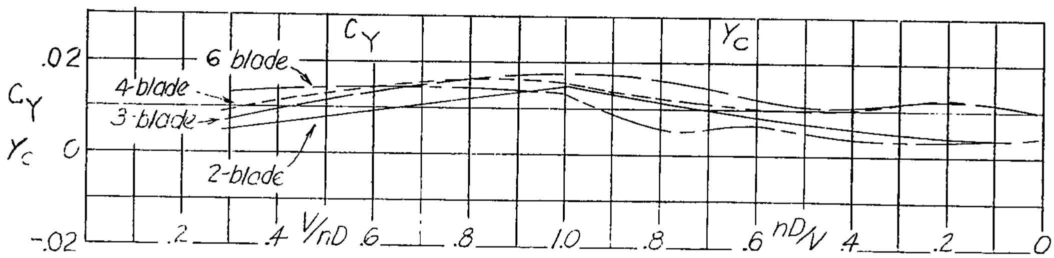


Figure 42.- Effect of pitch on side force. $\beta = 45°$.



(a) β = 25°.



(b) β = 45°.

Figure 43 – Effect of solidity on side force. θ = 10°

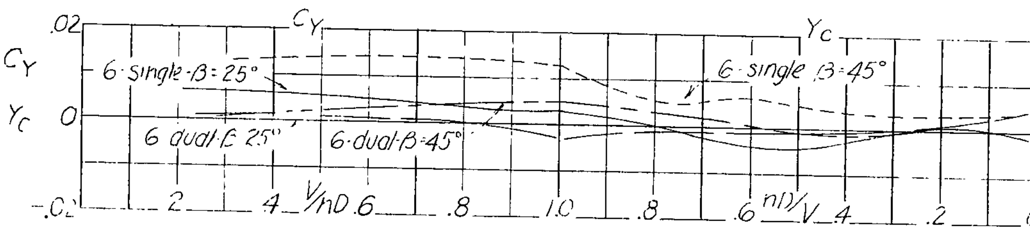


FIGURE 44. – Effect of dual rotation on side force for six blade propellers.

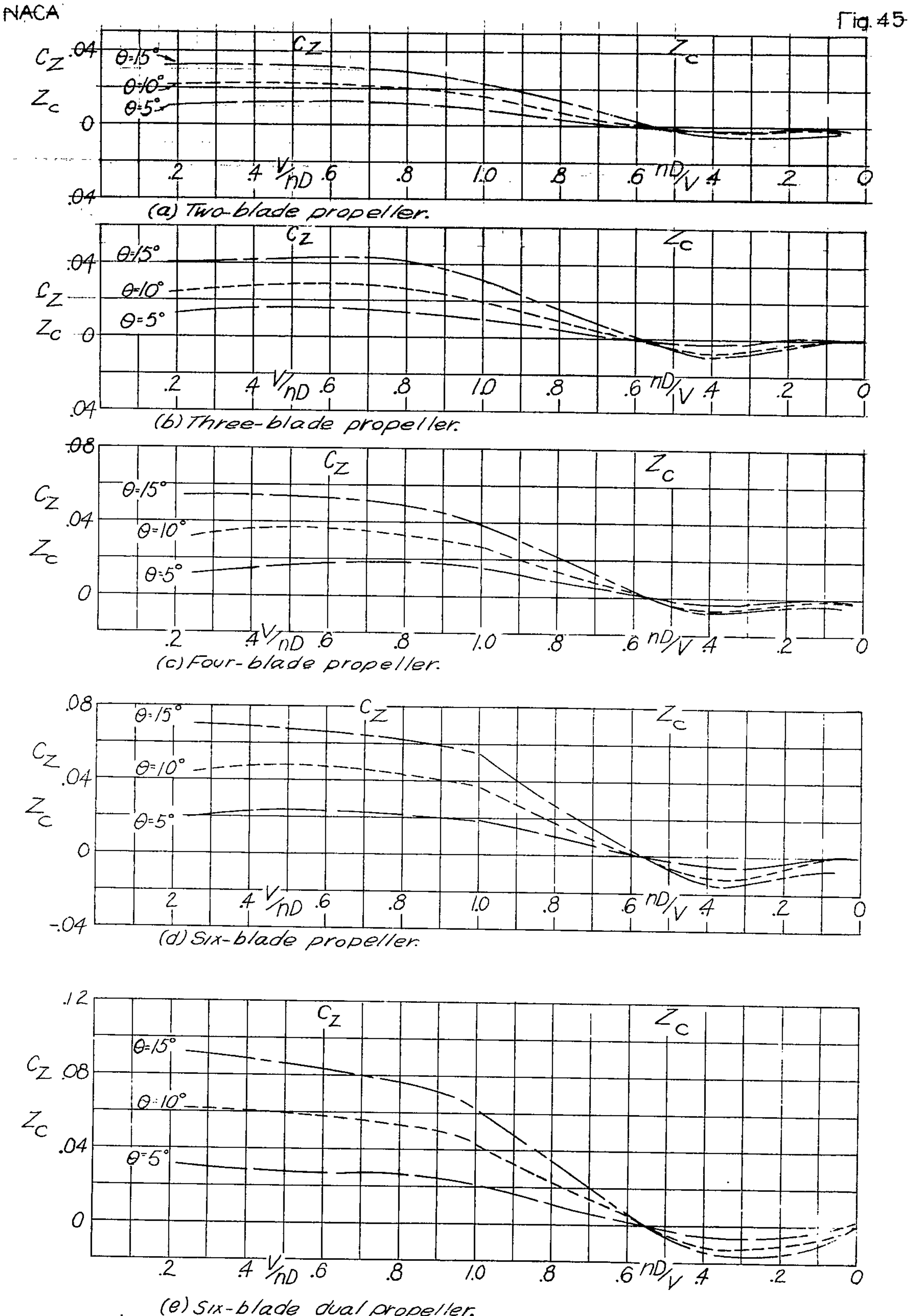


Figure 45.- Effect of pitch on vertical force. β=25°.

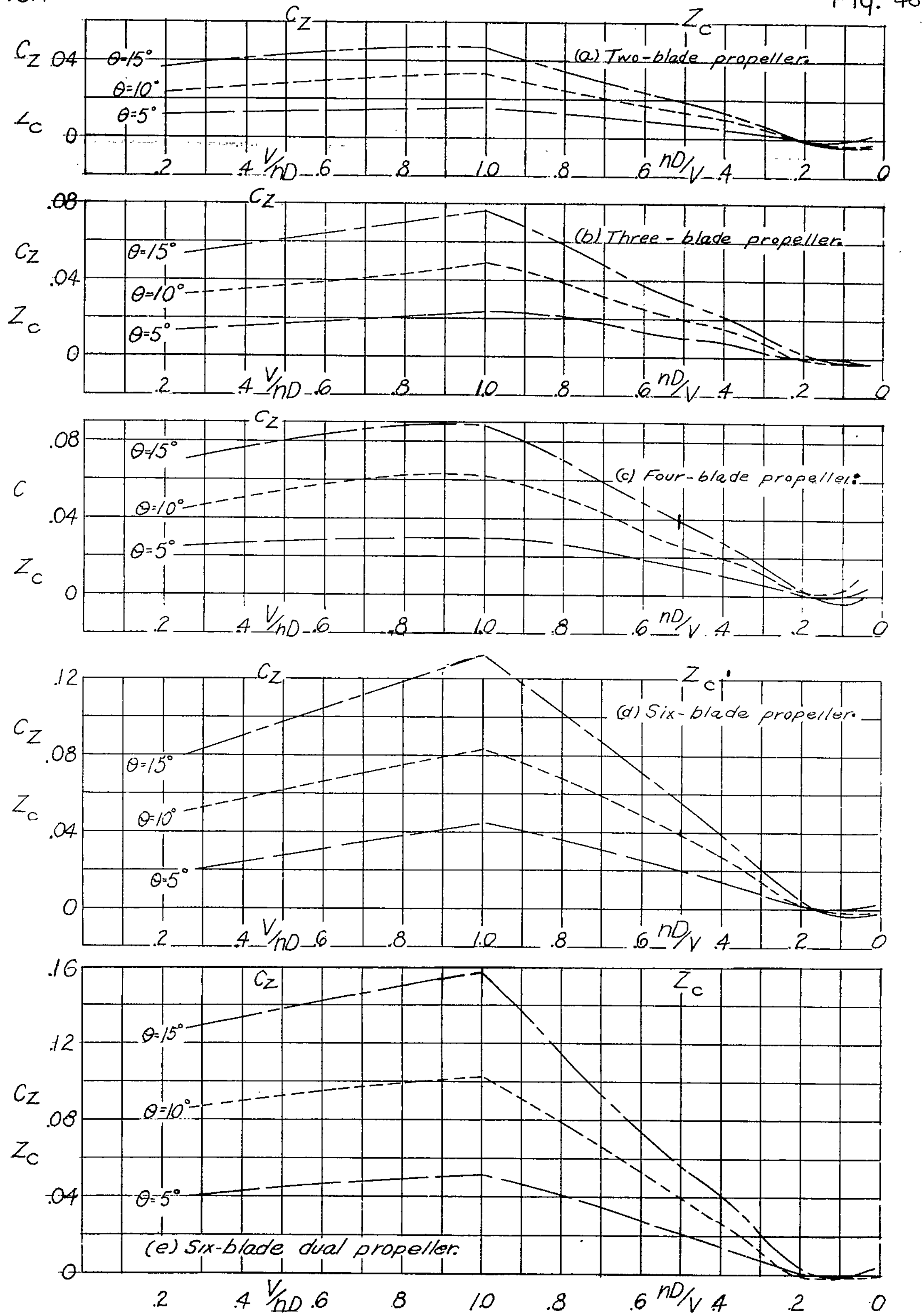


FIGURE 46.— Effect of pitch on vertical force. $\beta = 45°$

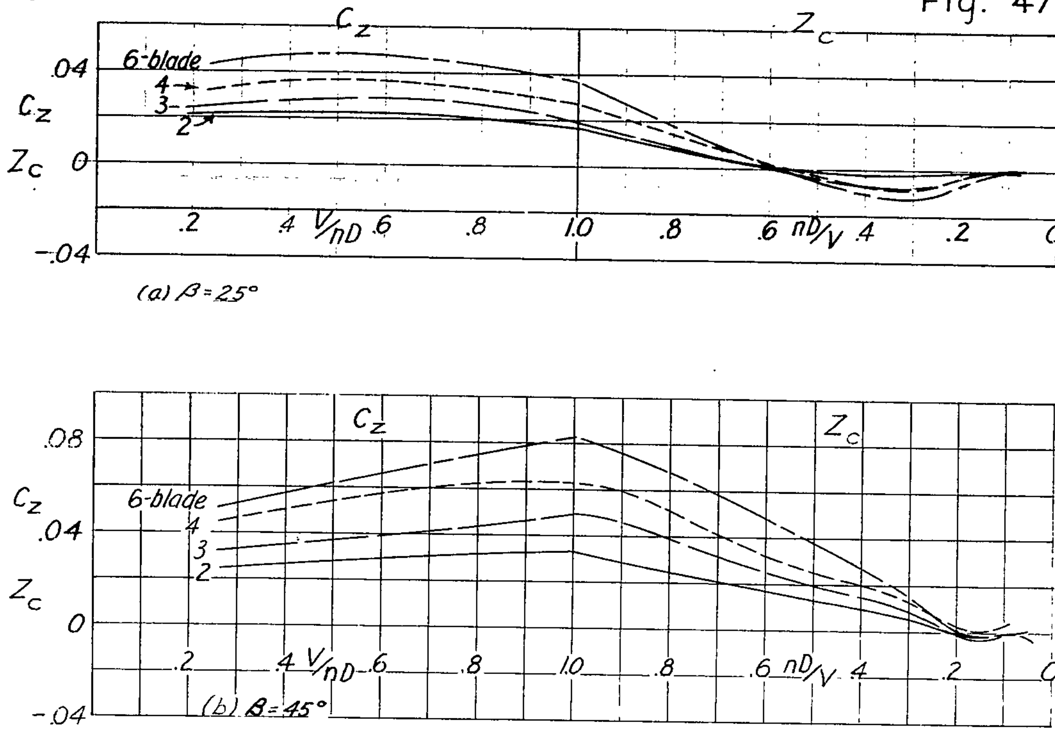


FIGURE 47.– Effect of solidity on vertical force. θ=10°

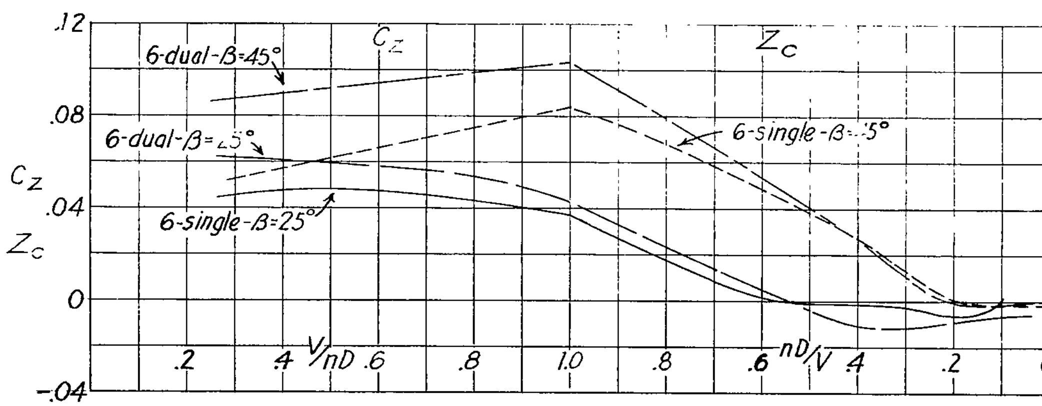


FIGURE 48.– Effect of dual rotation on vertical force for six-blade propellers.

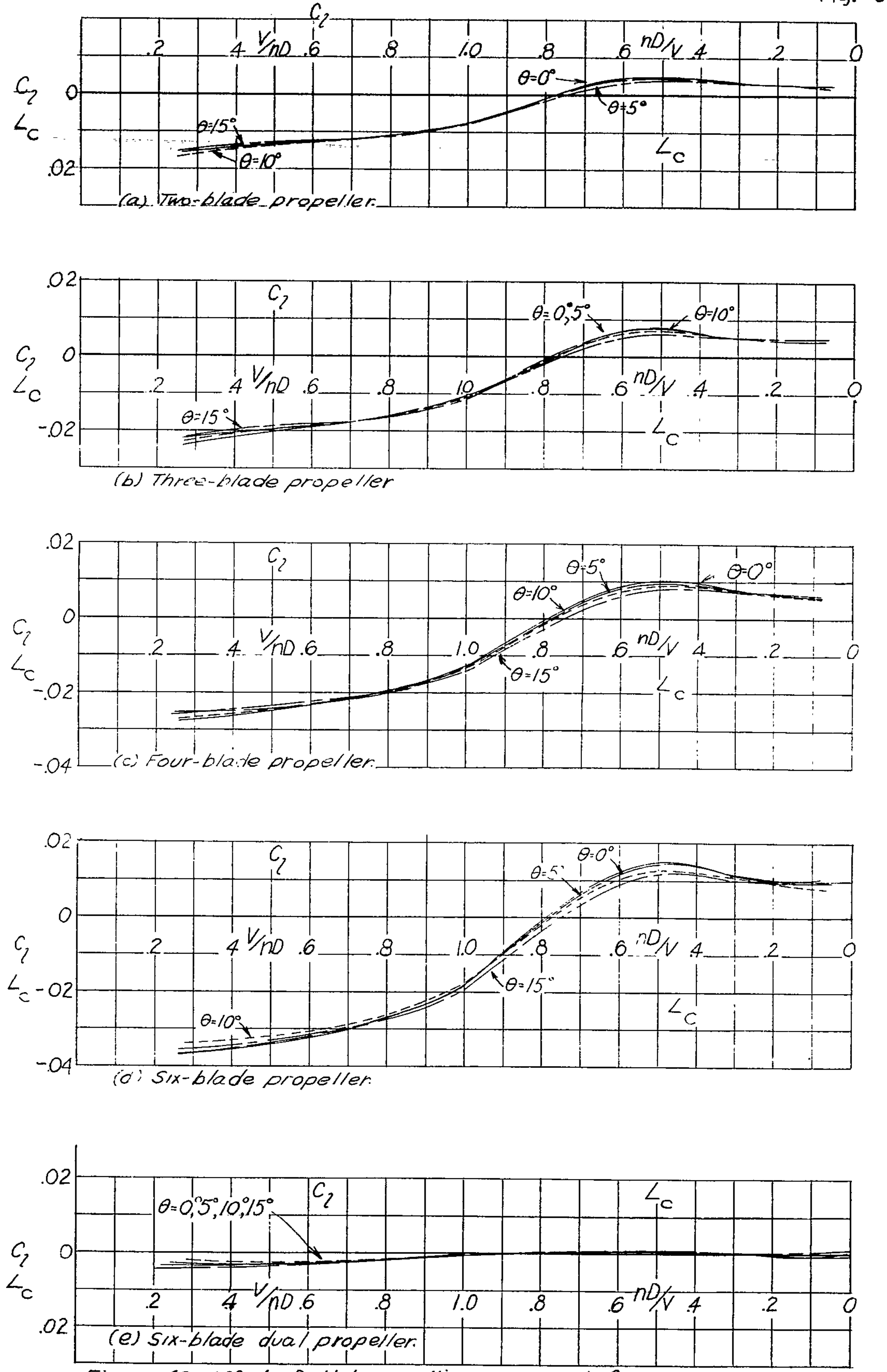


Figure 49.- Effect of pitch on rolling moment. β=25°.

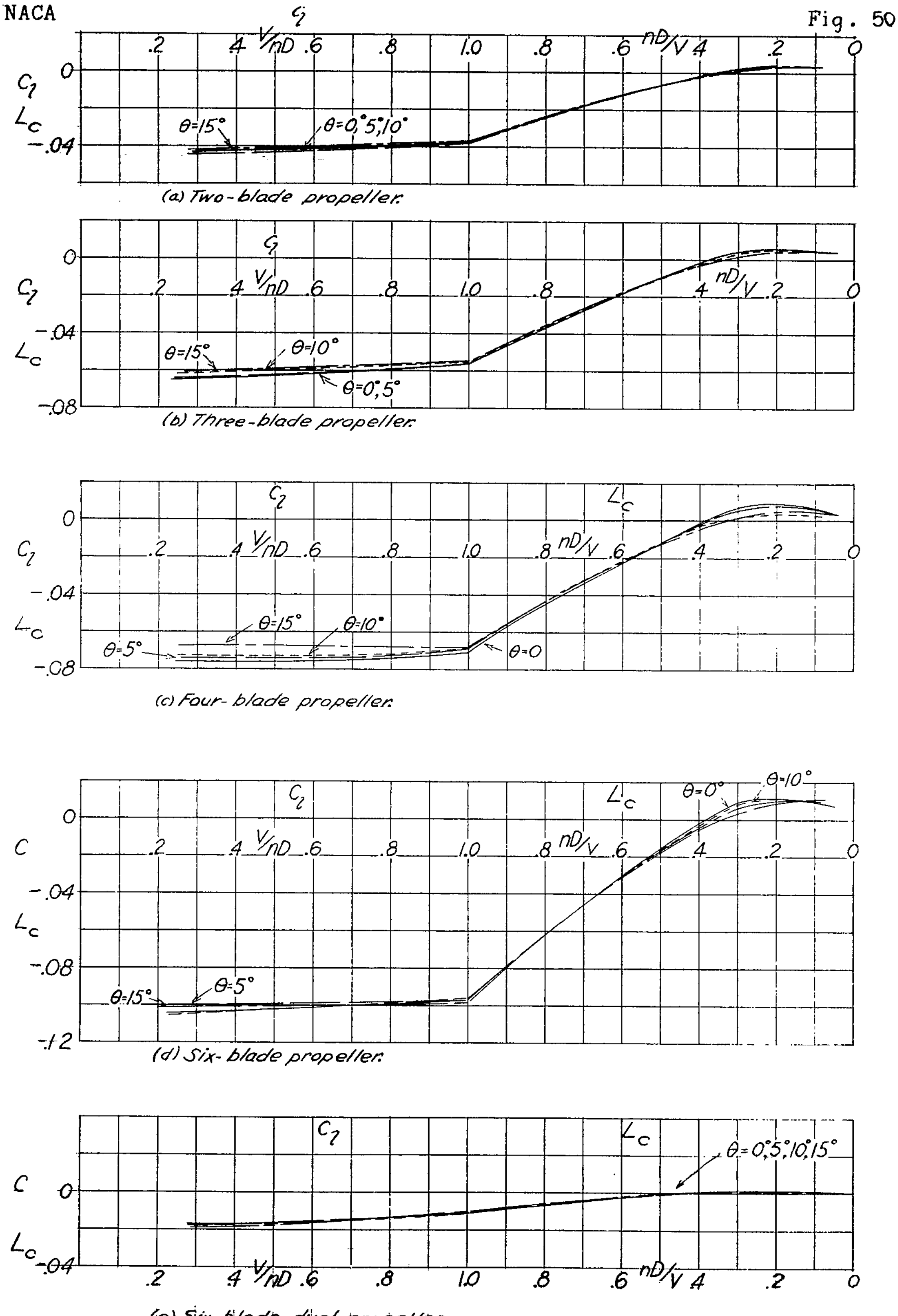


Figure 50.- Effect of pitch on rolling moment, β=45°

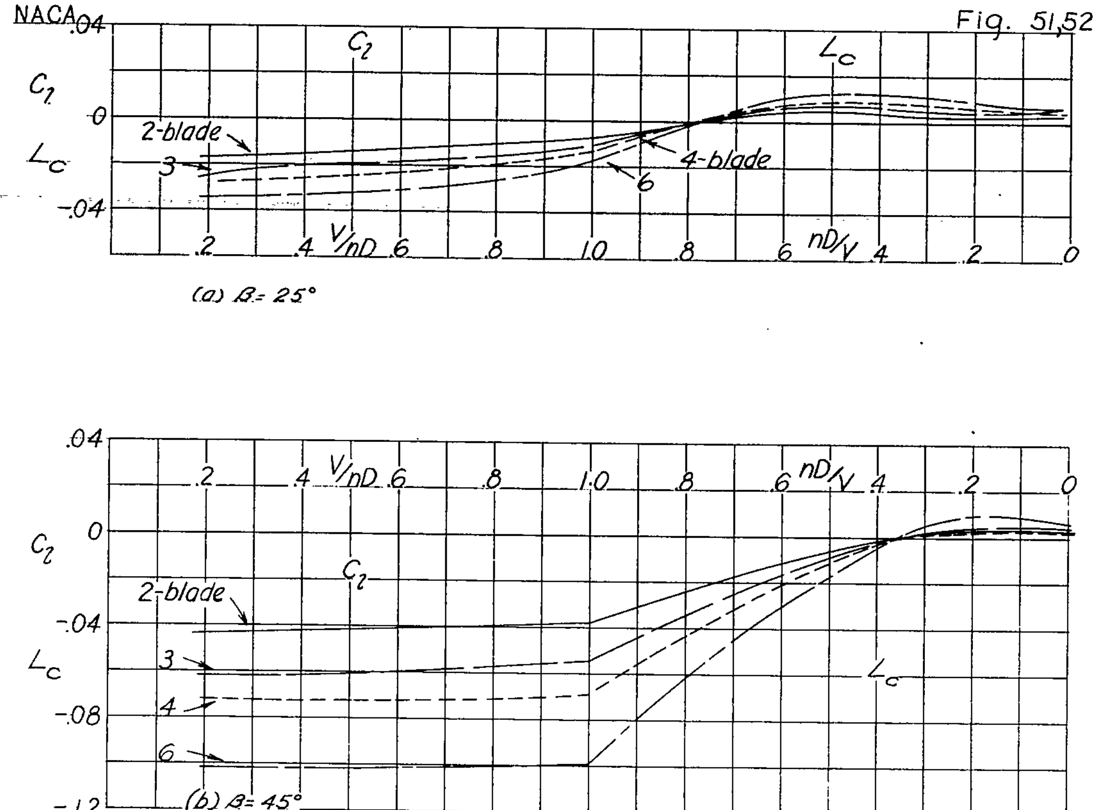


Figure 51.– Effect of solidity on rolling moment. θ=10°

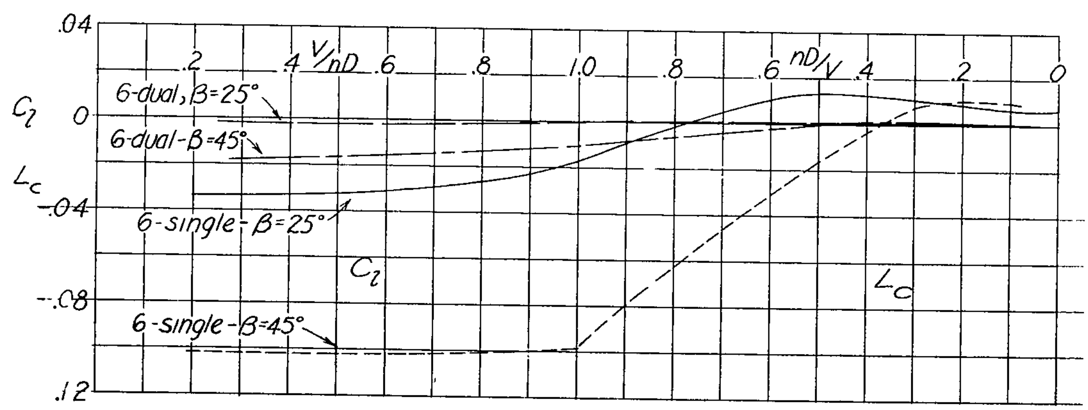


FIGURE 52. - Effect of dual rotation on rolling moment. θ=10°

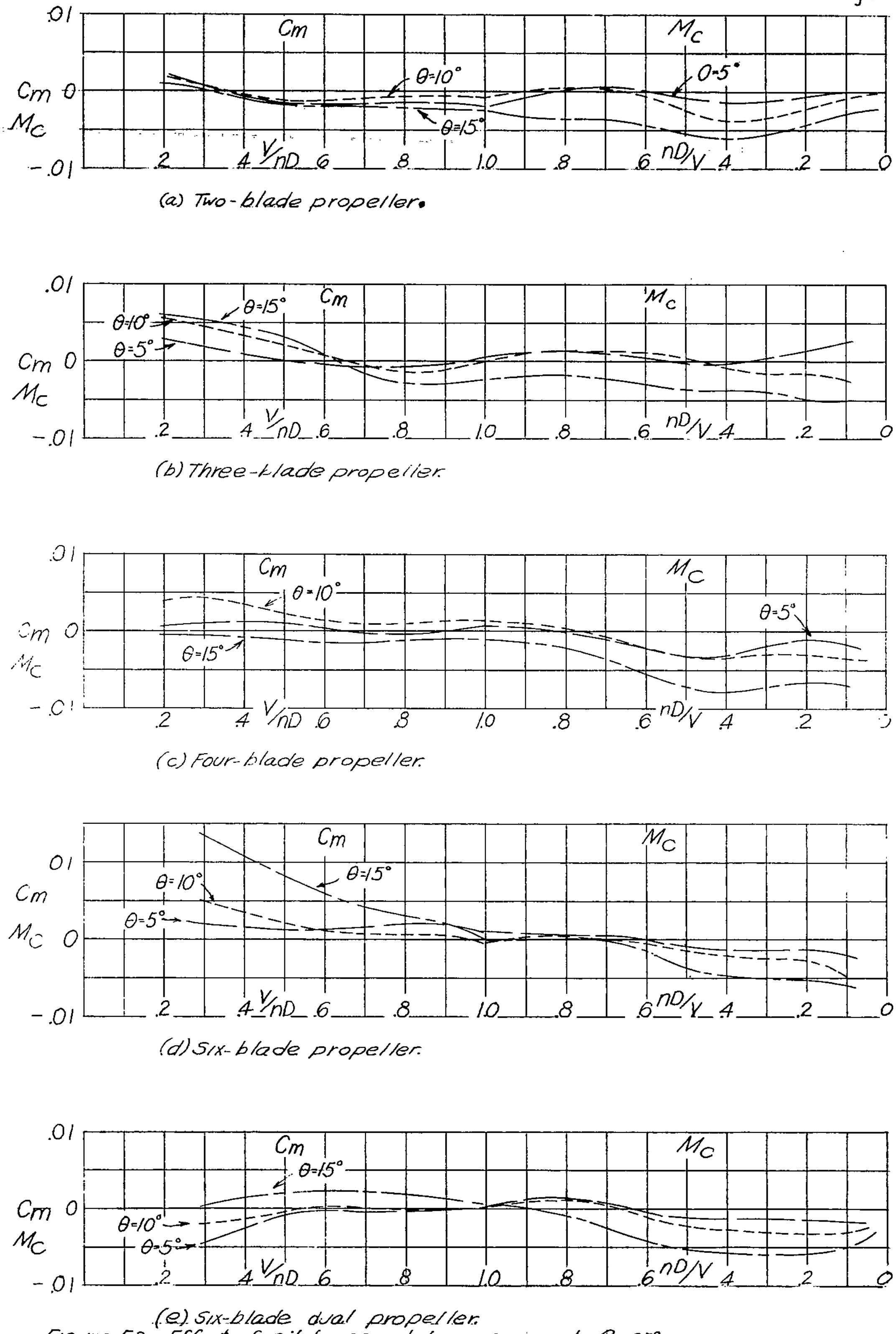
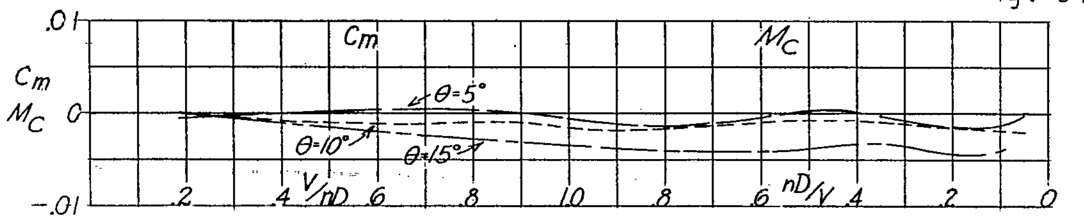
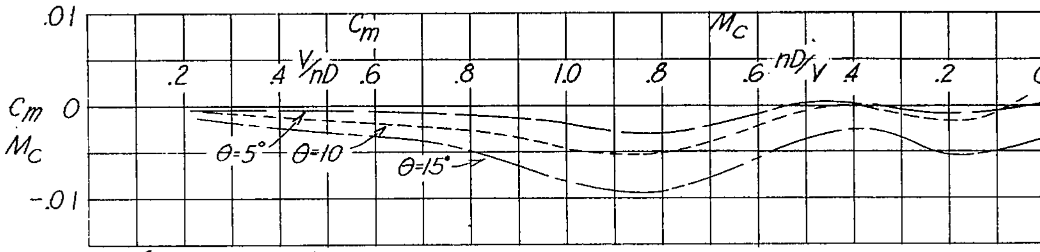


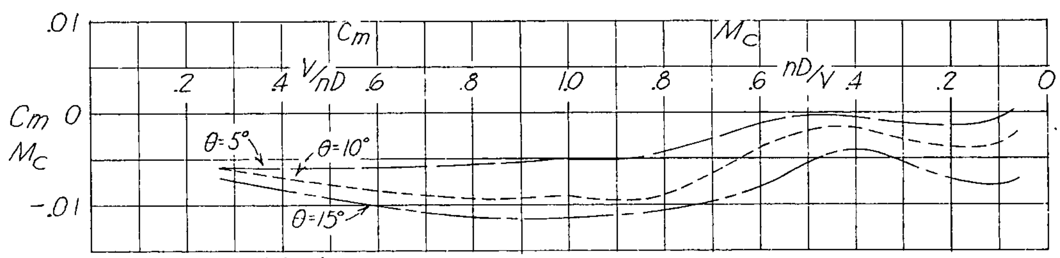
Figure 53.- Effect of pitch on pitching moment. β=25°.



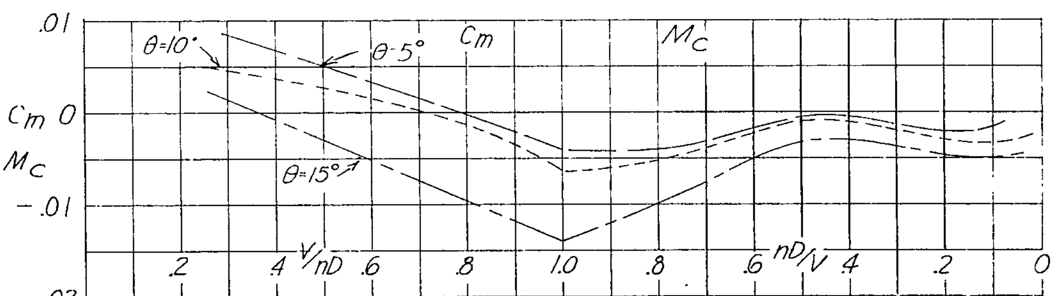
(a) Two-blade propeller.



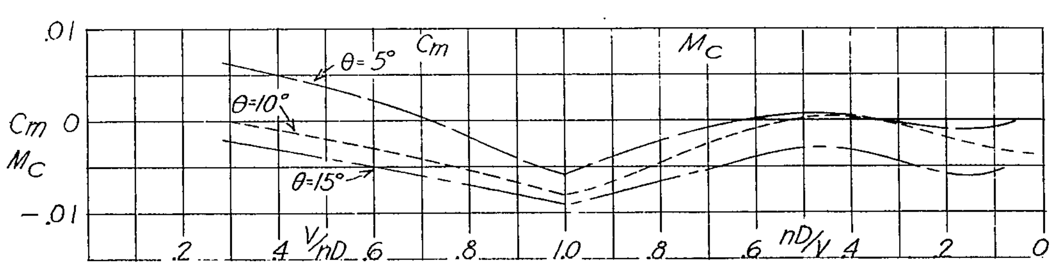
(b) Three-blade propeller.



(c) Four-blade propeller.



(d) Six-blade propeller.



(e) Six-blade dual propeller.

Figure 54.- Effect of pitch on pitching moment. β=45°.

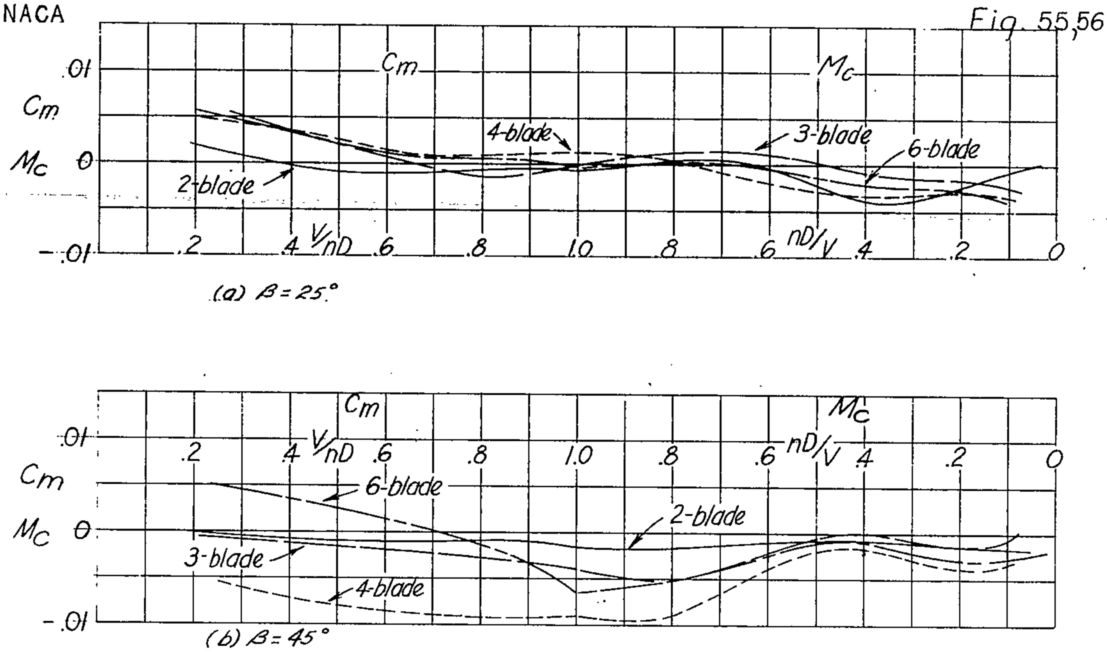


Figure 55.- Effect of solidity on pitching moment. θ = 10°

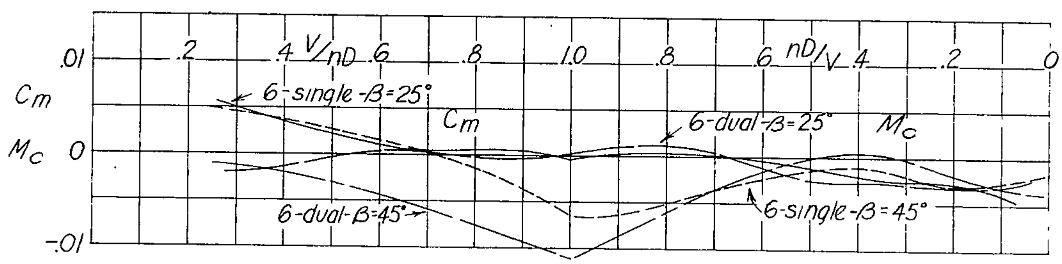
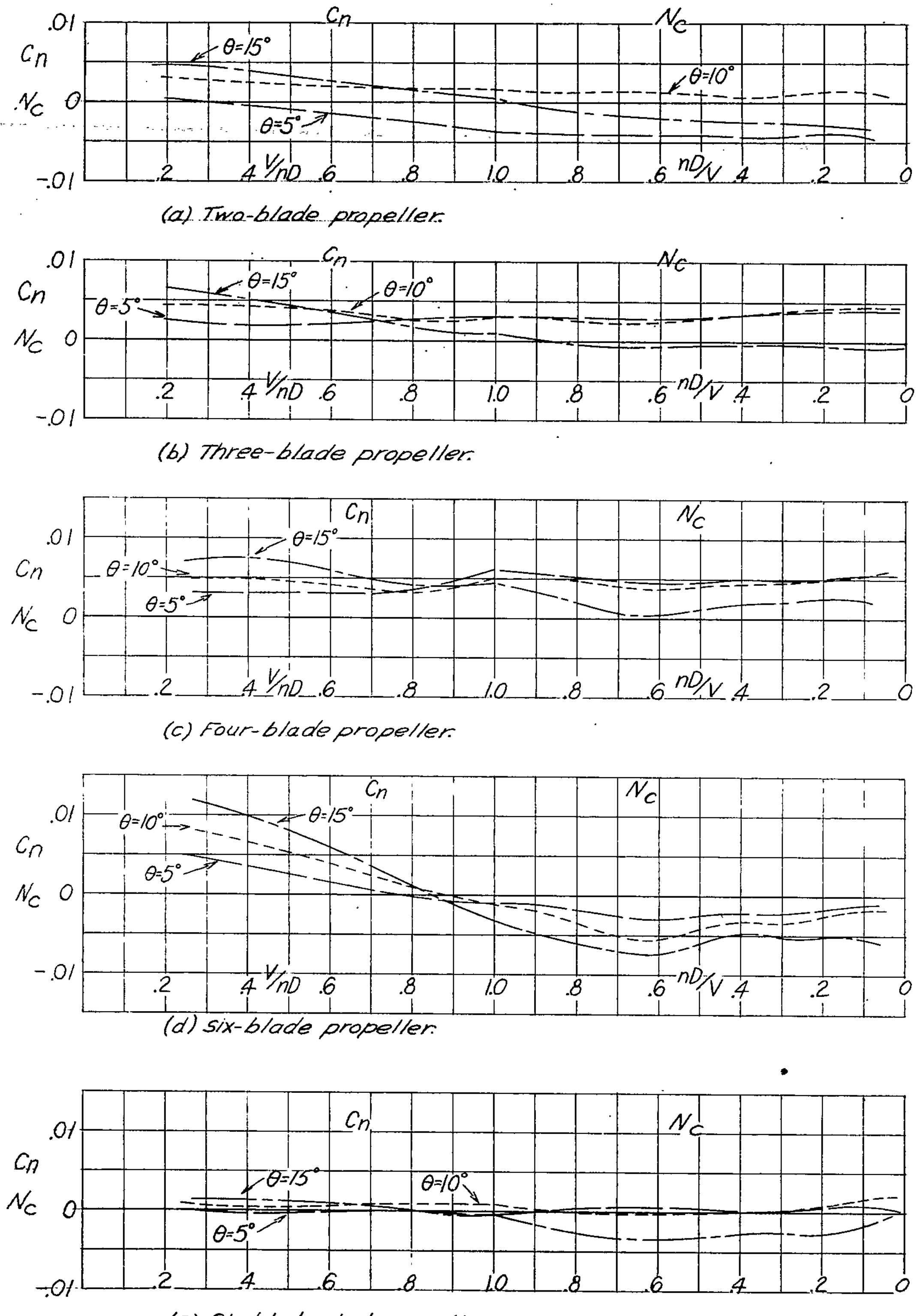


FIGURE 56.— *Effect of dual rotation on pitching moment for six-blade propellers.*



(a) Two-blade propeller.

(b) Three-blade propeller.

(c) Four-blade propeller.

(d) six-blade propeller.

(e) Six-blade dual propeller.

Figure 57.- Effect of pitch on yawing moment, β=25°.

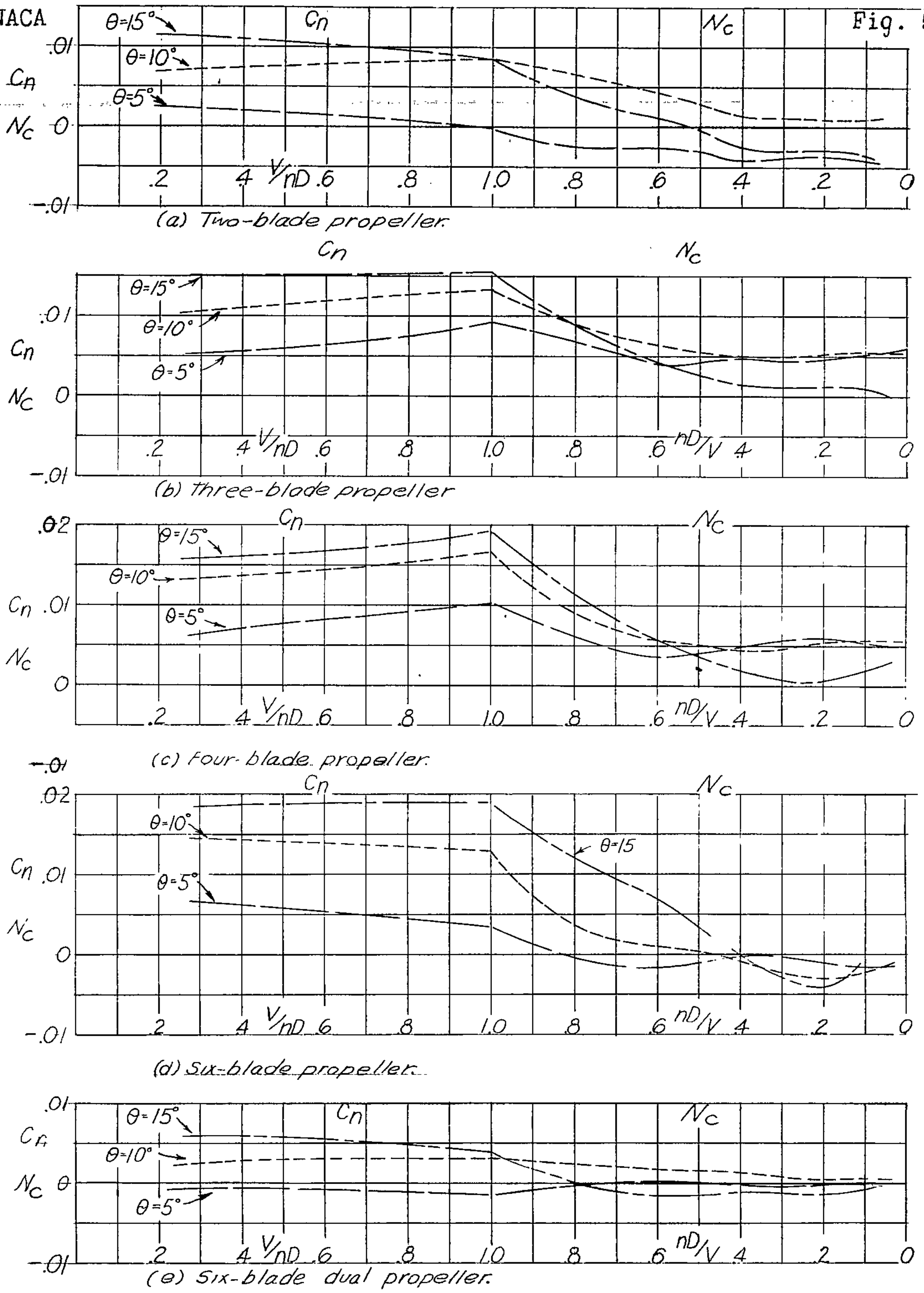


Figure 58.- Effect of pitch on yawing moment. β=45°

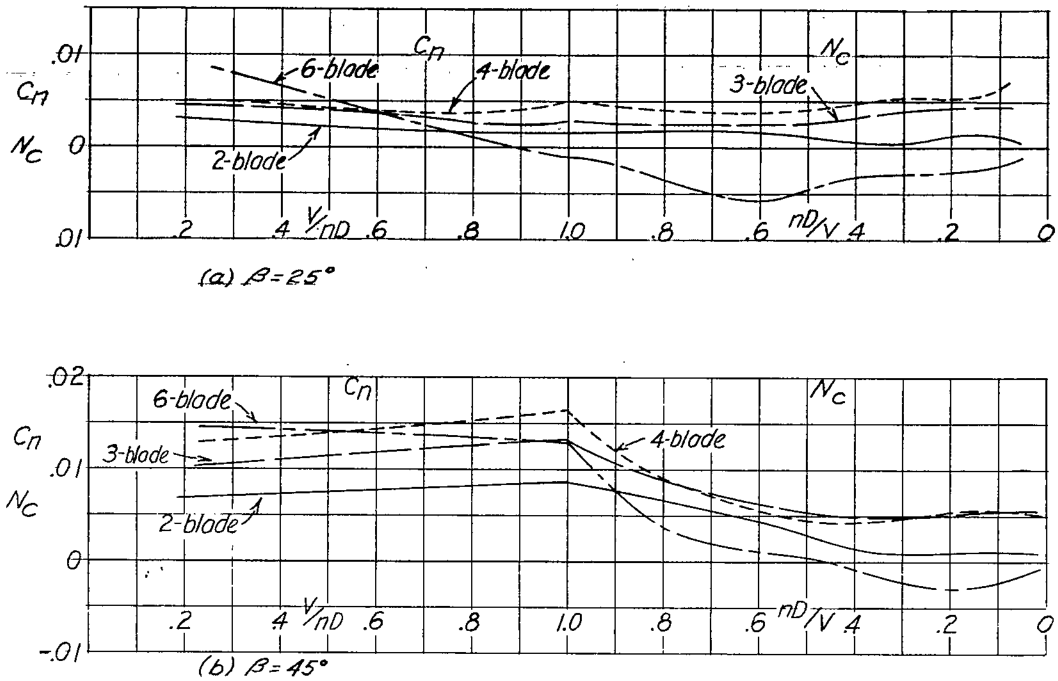


Figure 59.- Effect of solidity on yawing moment, θ=10°.

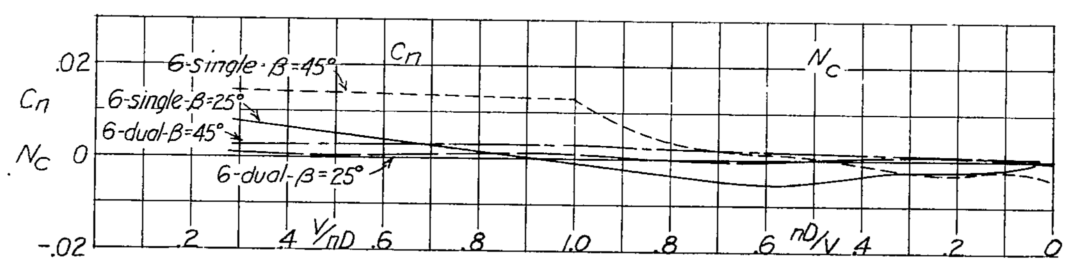


FIGURE 60.- Effect of dual rotation on yawing moment for six-blade propellers.

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5. Biermann, David, and Hartman, Edwin P.: Wind-Tunnel Tests of Four- and Six-Blade Single- and Dual-Rotating Tractor Propellers. NACA Rep. No. 747, 1942.